Lessons from *WMAP*

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JPL Colloquium
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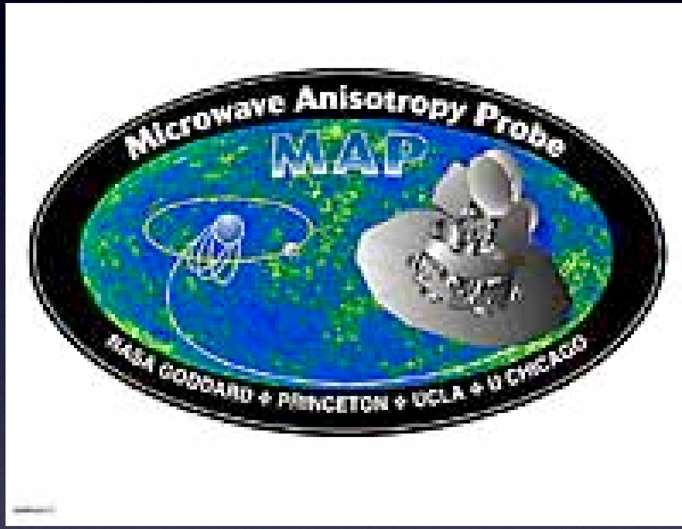
Outline:

- History (*WMAP*)
  - Spinning dust
  - Haze

- Digression on particle physics (i.e. why is the haze important?)

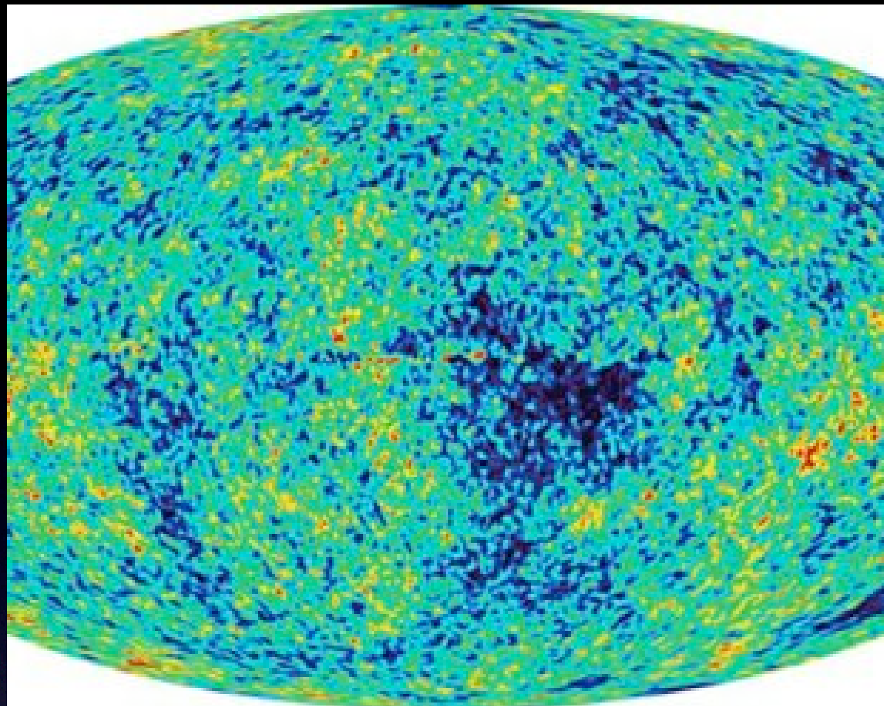
- The Future (*Planck*)
  - Refine the haze spectrum
  - Are the 2 FDS99 dust components "real"
  - New dust map (Akari, Planck, etc.)

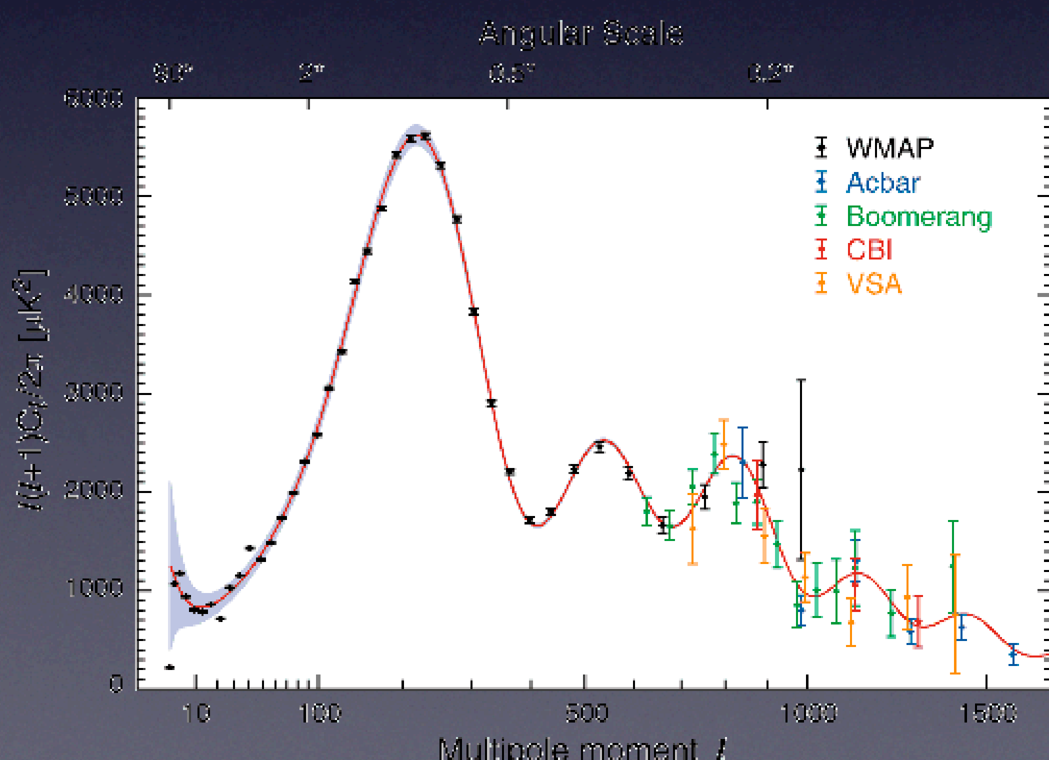
1. History



WMAP launch,
June 30, 2001

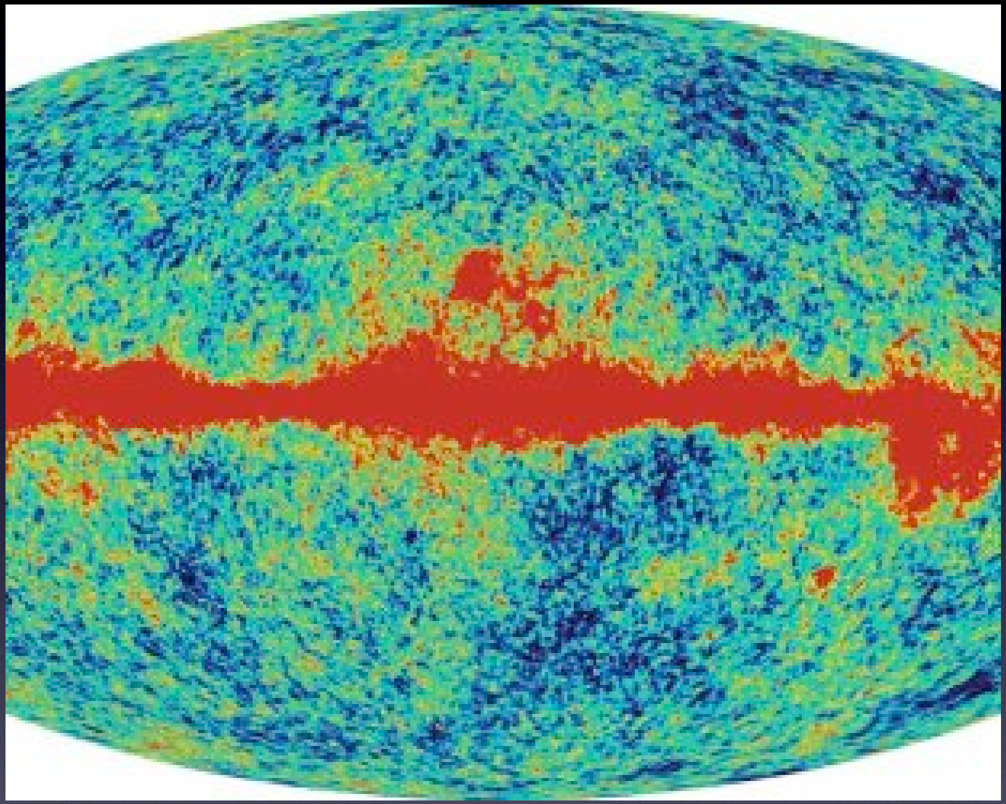
WMAP fulfilled its cosmological promise...

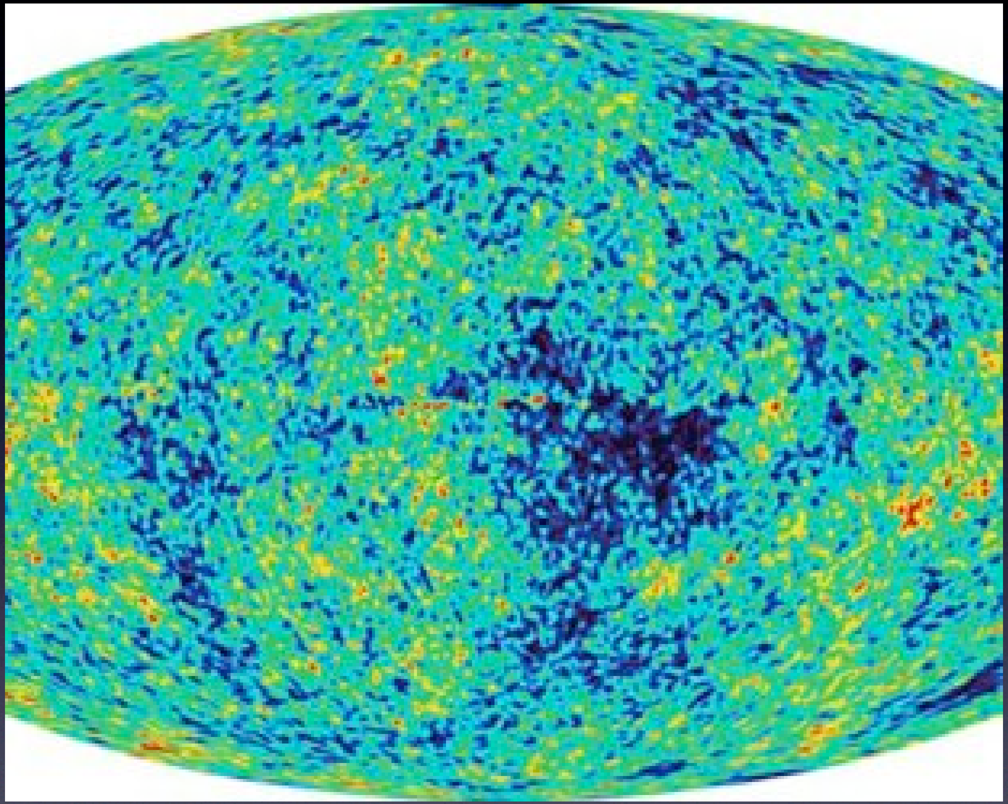




WMAP Cosmological Parameters Model: lcdm Data: wmap+sdss	
$10^2\Omega_b h^2$	$2.230^{+0.071}_{-0.070}$
$\Delta^2_{\mathcal{R}}(k = 0.002/\mathrm{Mpc})$	$(24.1 \pm 1.3) \times 10^{-10}$
h	0.710 ± 0.026
H_0	71.0 ± 2.6 km/s/Mpc
$n_s(0.002)$	$0.948^{+0.016}_{-0.015}$
$\Omega_b h^2$	$0.02230^{+0.00071}_{-0.00070}$
Ω_Λ	0.735 ± 0.030
Ω_m	0.265 ± 0.030
$\Omega_m h^2$	$0.1327^{+0.0063}_{-0.0064}$
σ_8	$0.772^{+0.040}_{-0.041}$
A_{SZ}	$0.93^{+0.64}_{-0.61}$
t_0	13.77 ± 0.15 Gyr
τ	$0.080^{+0.029}_{-0.030}$
θ_A	$0.5950^{+0.0020}_{-0.0019}$ °
z_r	$10.3^{+2.6}_{-2.7}$

… but missed a few things about foregrounds





WMAP Q band (41 GHz)

For optimal modeling, a sophisticated technique is useful.

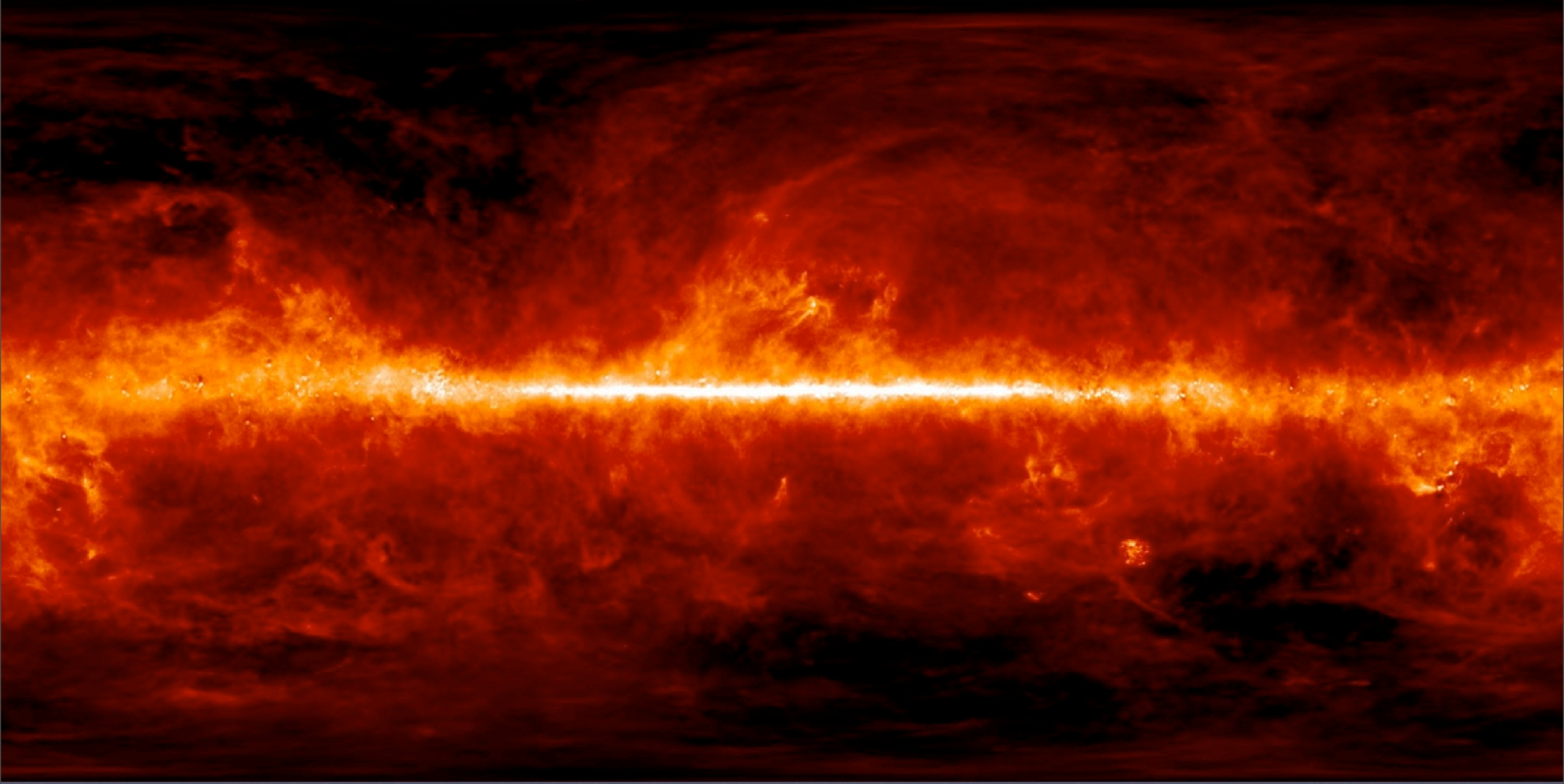
For discovering the unexpected, a simple (i.e. completely understood) technique may be better.

The WMAP team was primarily interested in CMB cosmology (obviously!) and tended towards the sophisticated.

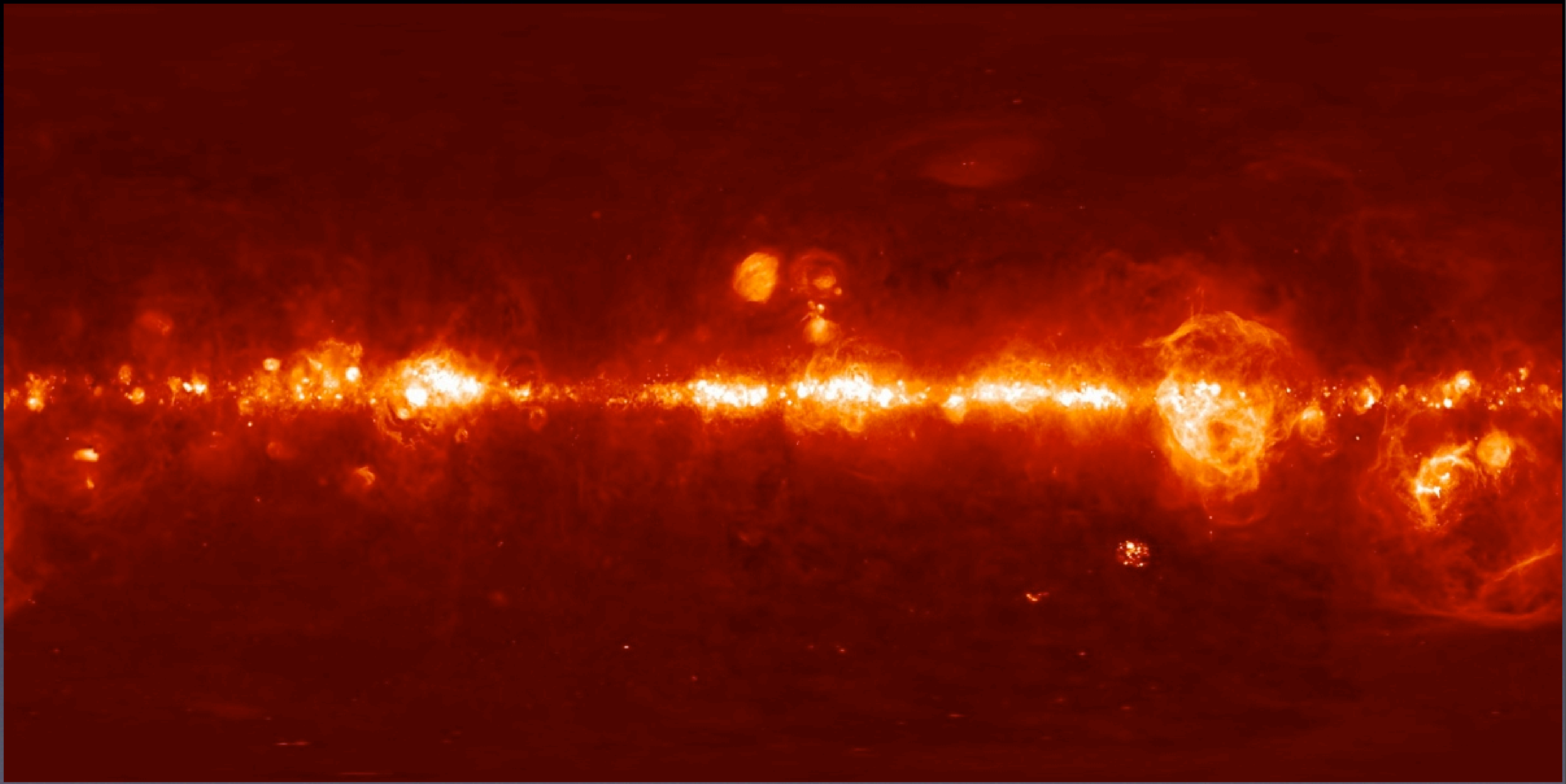
I was interested in pushing knowledge of foregrounds, and opted for simplicity.

The simplest possibility is a multilinear regression with externally derived templates.

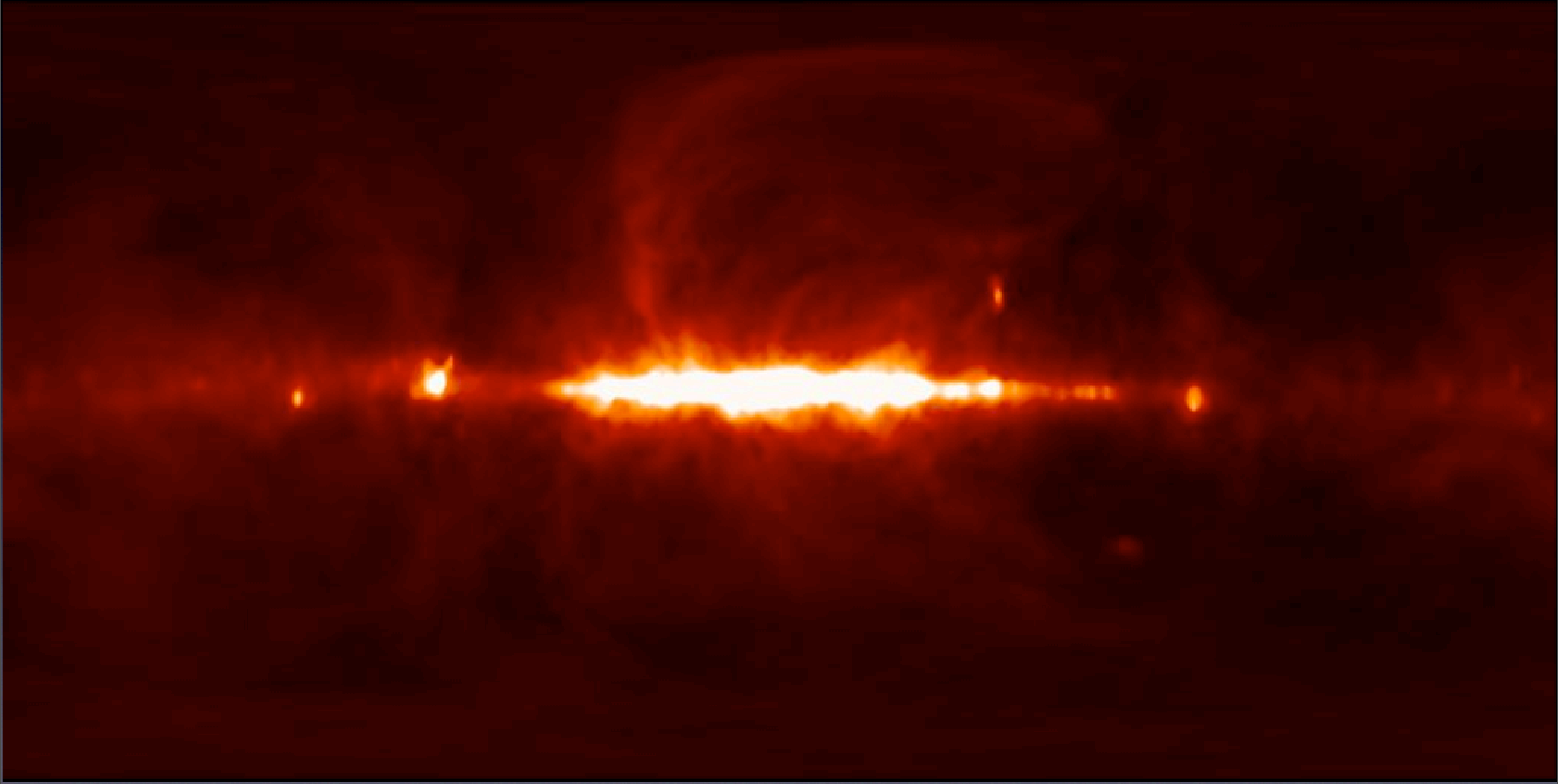
Interstellar Dust from IRAS, DIRBE (Finkbeiner et al. 1999) Map extrapolated from 3 THz (100 micron) with FIRAS.

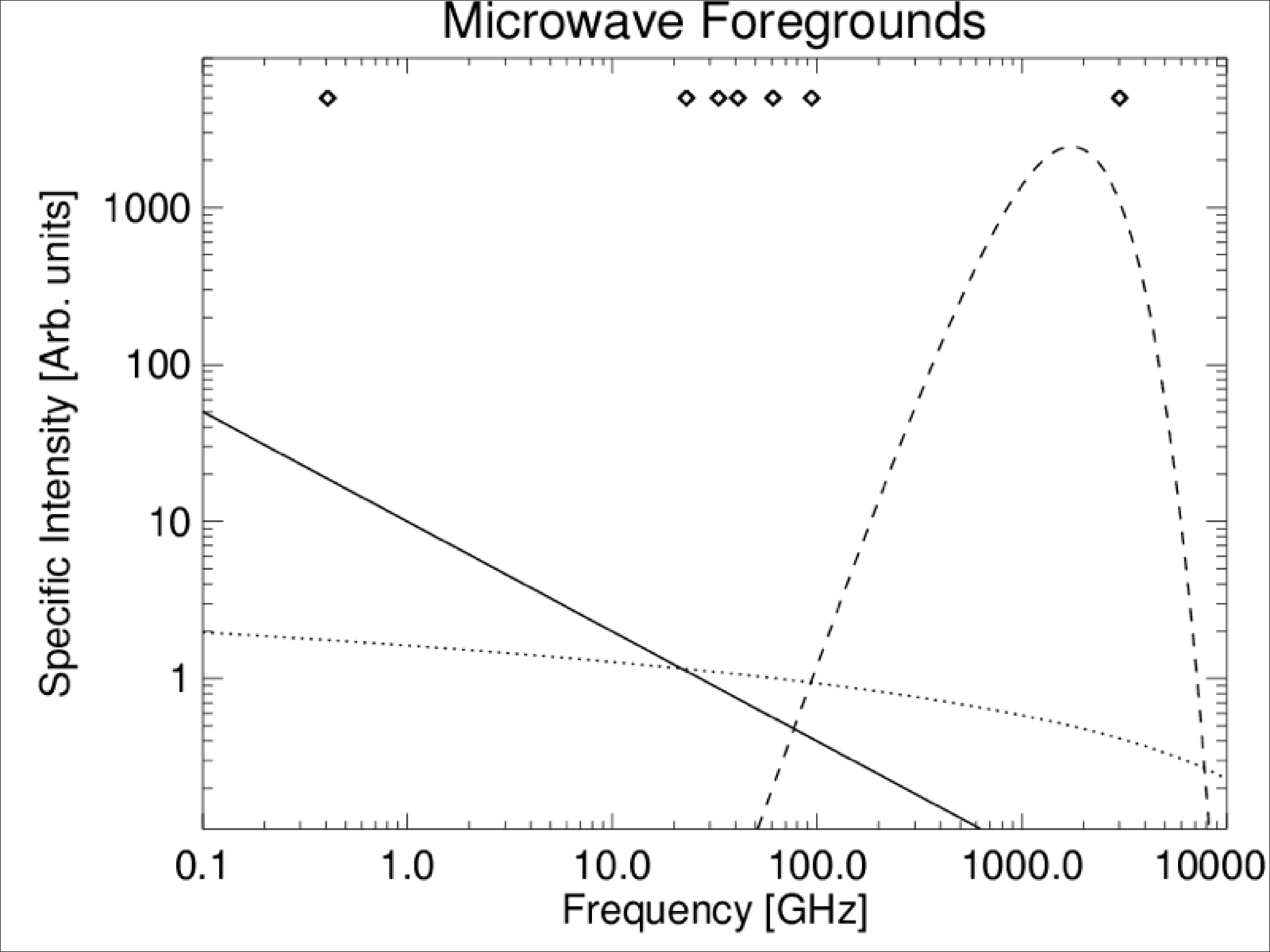


Ionized Gas from WHAM, SHASSA, VTSS (Finkbeiner 2003)
H-alpha emission measure goes as thermal bremsstrahlung.



Synchrotron at 408 MHz (Haslam et al. 1982)





Microwave Foregrounds
Specific Intensity [Arb. units]
1000
100
10
1
0.1
1.0
10.0
100.0
1000.0
10000
Frequency [GHz]

There is also “spinning dust” emission,
i.e. electric dipole emission from rapidly rotating small dust grains.

This emission is spatially (very approximately) similar to the thermal dust, but spectrally different.

(Kogut et al 1996; Draine & Lazarian 1998;
de Oliveira-Costa et al., 1998,1999,2000,2002,2004;
Finkbeiner et al. 2002, 2003, 2004, etc...)
Casassus et al. (2006) Davies et al. (2006) Dickinson et al (2006)
Rafikov (2006) Boughn & Pober (2007) Dickinson et al (2007)
Scaife et al (2007) Dobler & Finkbeiner (2008)
Miville-Deschenes et al (2008)

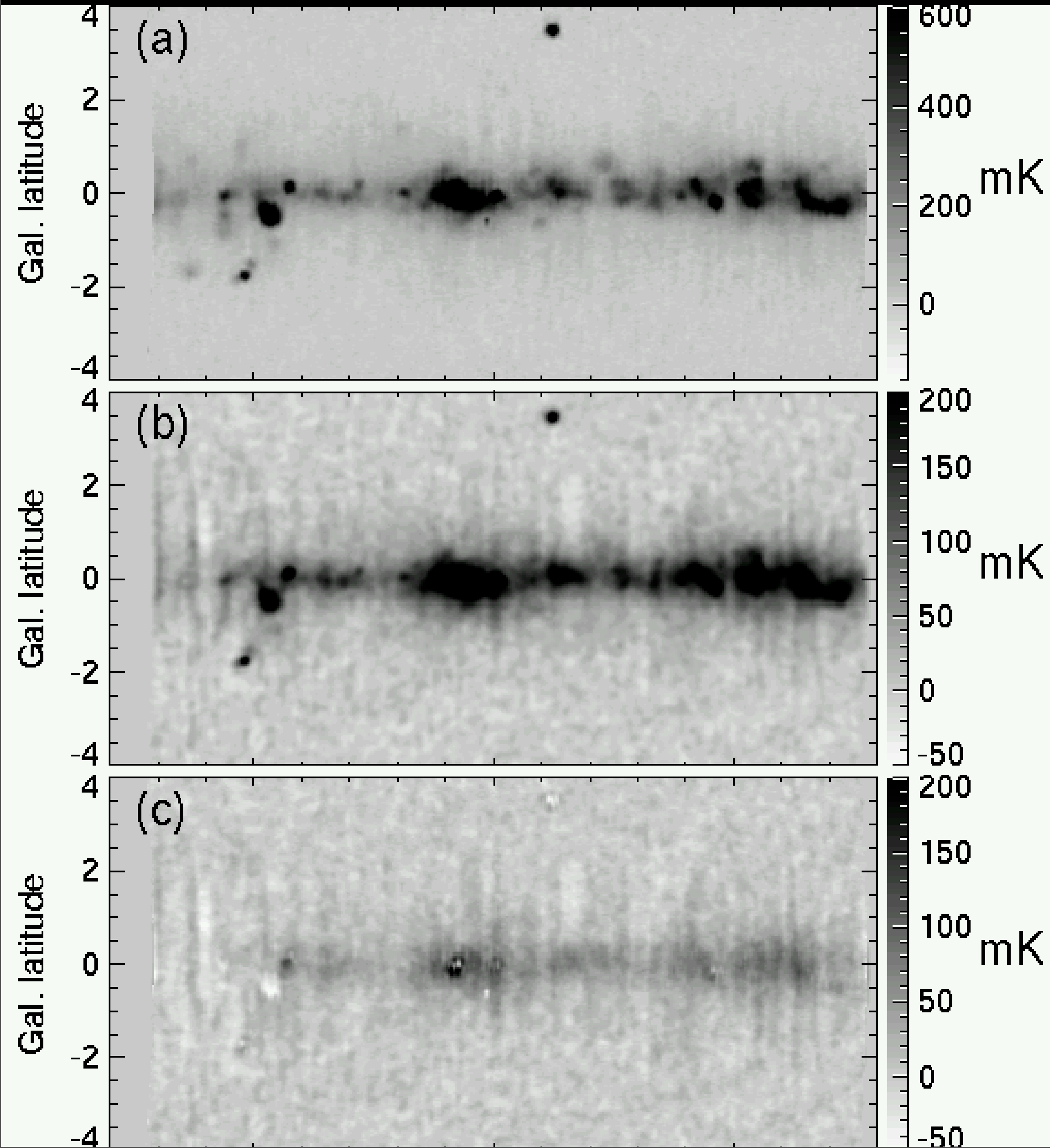
Theoretical work by Ysard & Verstraete; Ali-Hamoud & Hirata, etc...

The status of spinning dust was quite uncertain in early 2003, at the time of the 1st year WMAP data release. We had:

Kogut etal (1996) - DMR 31 GHz
de Oliveira-Costa etal (1998) - Saskatoon 30,40 GHz
Leitch etal (1997) - OVRO 14, 31 GHz

These led to the Draine & Lazarian (1998) model.

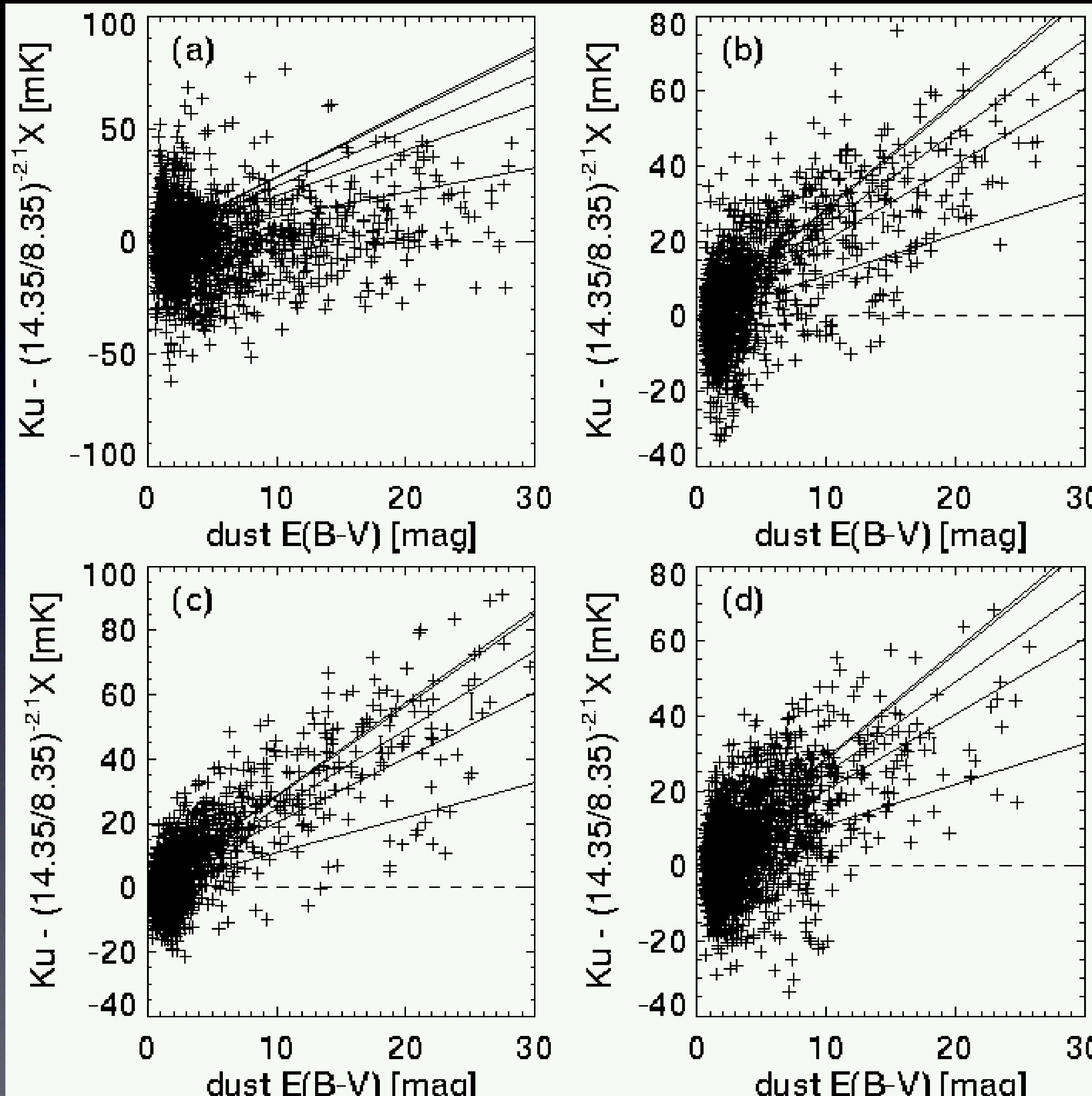
My involvement began with the GB 140 foot data on two clouds (2002) and the GB Galactic Plane survey with Langston & Minter (2004).



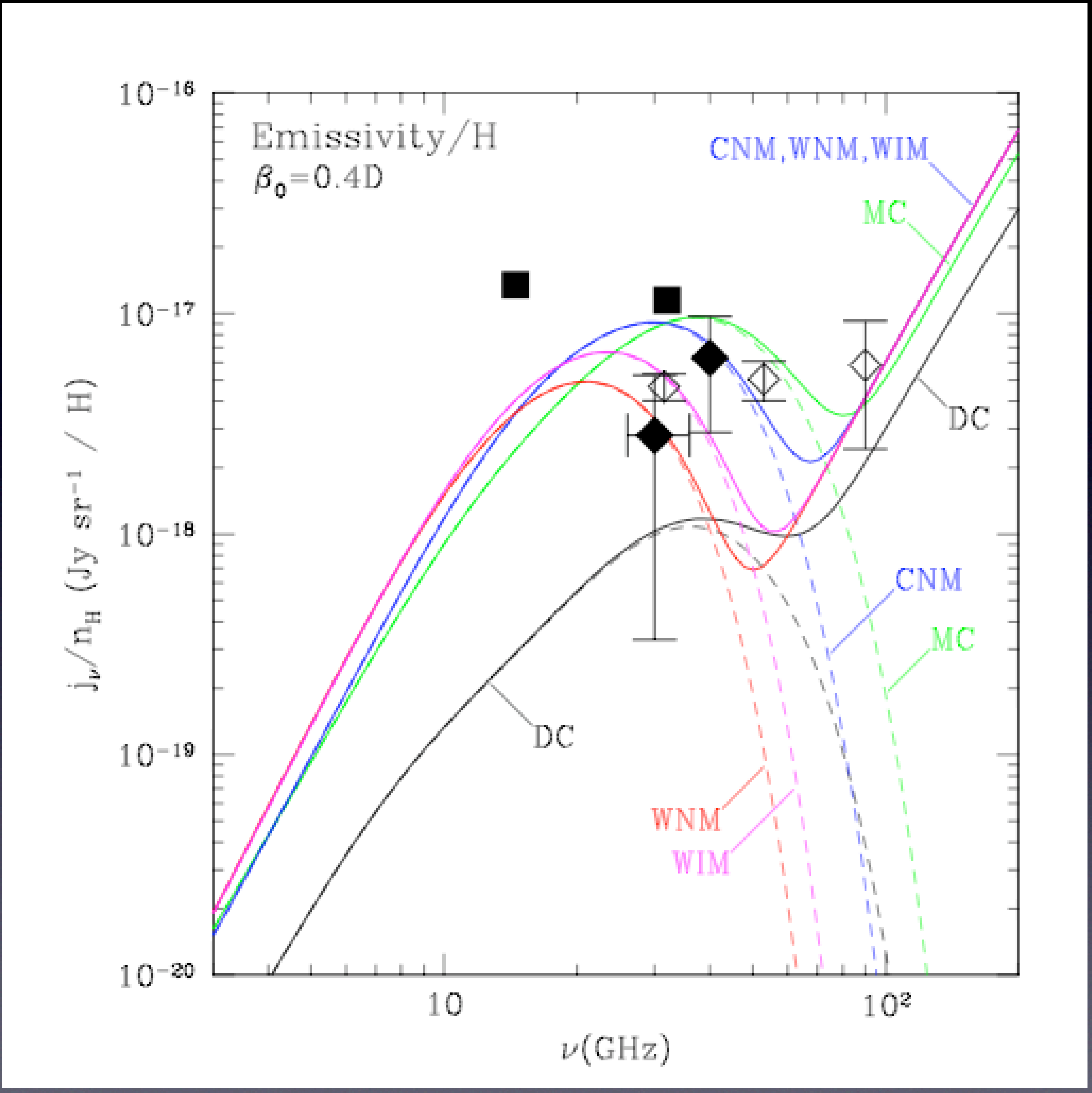
8.35 GHz

14.35 GHz

Green Bank Survey
Longitude 30 slice
Finkbeiner, Langston, &
Minter (2004)



Finkbeiner, Langston, & Minter (2004)



Draine & Lazarian (1998)

My opinion was that the GB 8 & 14 GHz survey nailed the problem, and that spinning dust (or something very much like it) was real.

The null hypothesis was dead.

Imagine my surprise when...

First Year *Wilkinson Microwave Anisotropy Probe* (*WMAP*) Observations: Foreground Emission

C. L. Bennett[2], R. S. Hill[3], G. Hinshaw[2], M. R. Nolta[4], N. Odegard[3], L. Page[4], D. N. Spergel[5], J. L. Weiland[3], E. L. Wright[6], M. Halpern[7], N. Jarosik[4], A. Kogut[2], M. Limon[2,8], S. S. Meyer[9], G. S. Tucker[2,8,10], E. Wollack[2]

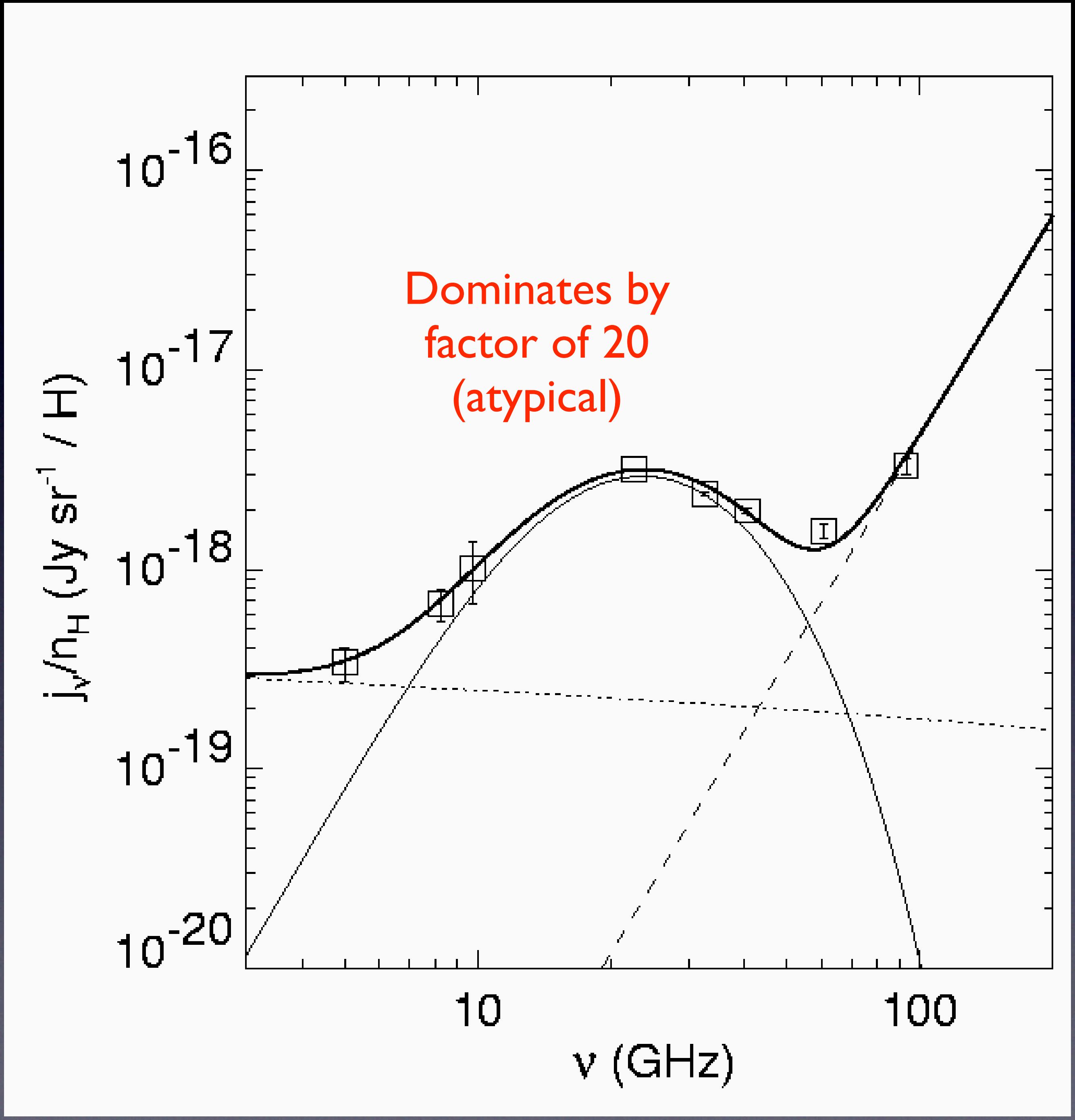
trapped in the Galactic potential long enough to suffer synchrotron and inverse Compton energy losses and hence a spectral steepening. The synchrotron index is steeper in the *WMAP* bands than in lower frequency radio surveys, with a spectral break near 20 GHz to $\beta_s < -3$. The modeled thermal dust spectral index is also steep in the *WMAP* bands, with $\beta_d \approx 2.2$. Our model is driven to these conclusions by the low level of total foreground contamination at ~ 60 GHz. Microwave and Hα measurements of the ionized gas agree well with one another at about the expected levels. Spinning dust emission is limited to $< 5\%$ of the Ka-band foreground emission.

A catalog of 208 point sources is presented. The reliability of the catalog is 98%, i.e., we expect five of the 208 sources to be statistically spurious. The mean spectral index of the point sources is $\alpha \sim 0$ ($\beta \sim -2$). Derived source counts suggest a contribution to the anisotropy power from unresolved sources of $(15.0 \pm 1.4) \times 10^{-3}$ μK^{2}sr at Q-band and negligible levels at V-band and W-band. The Sunyaev-Zeldovich effect is shown to be a negligible "contamination" to the maps.

Subject headings: cosmic microwave background, cosmology: observations, Galaxy: structure, (ISM:) cosmic rays, ISM: structure, Galaxy: general, Galaxy: halo, (cosmology:) diffuse radiation, radio continuum: ISM

As it turns out, L1622 appears in WMAP also:

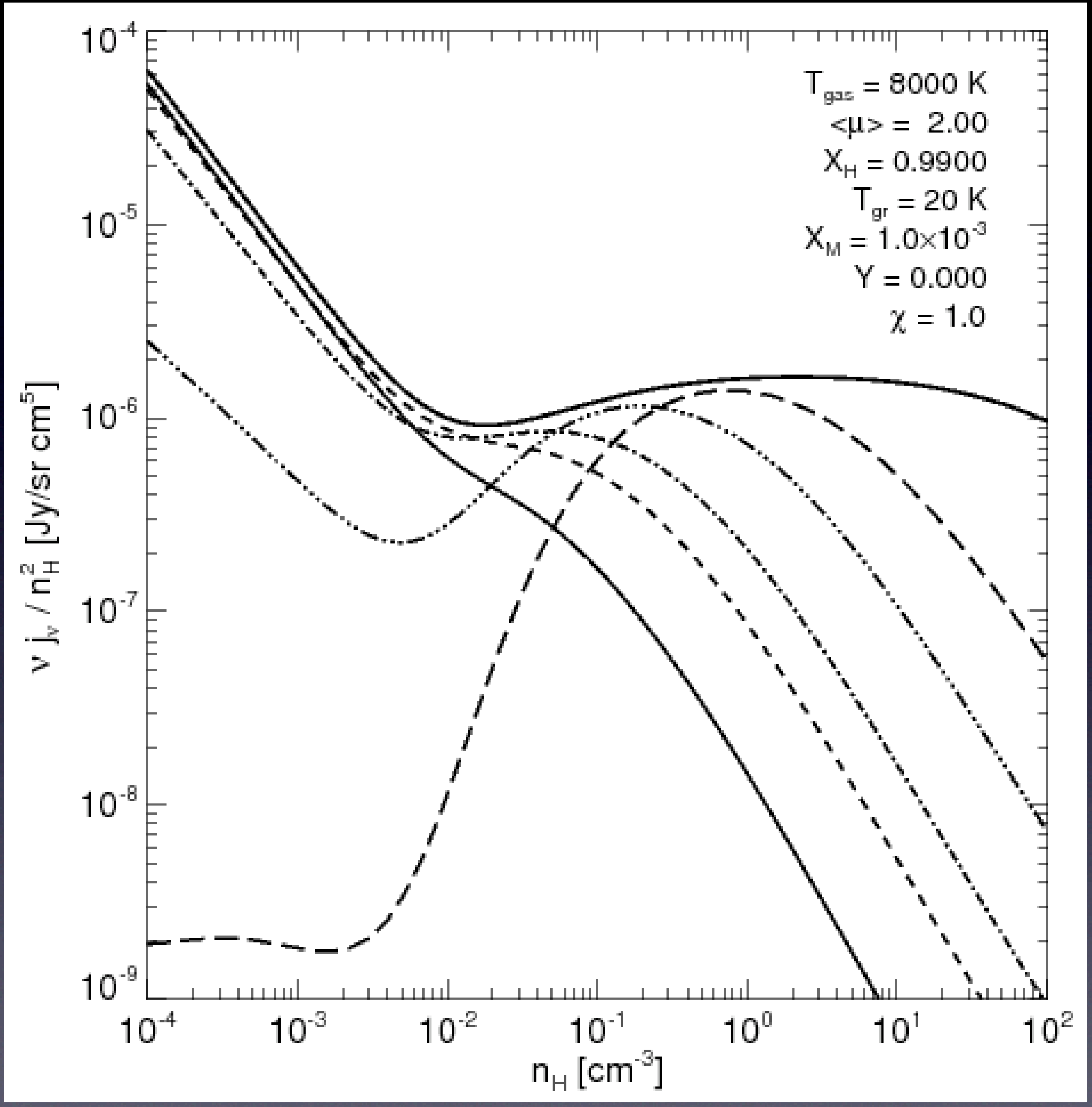
Lynds 1622 spectrum (Finkbeiner 2003)



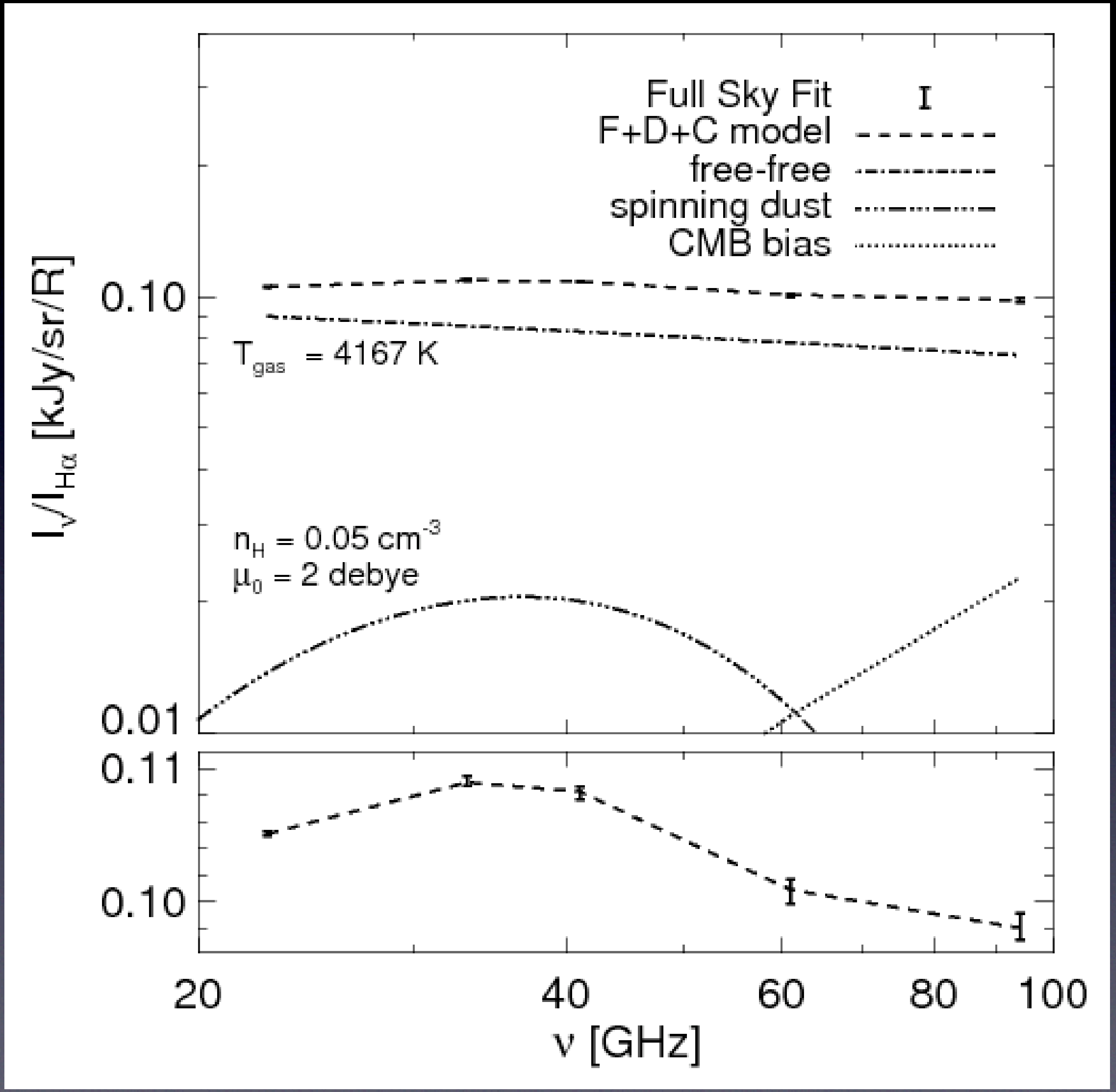
In the end, we found spinning dust emission looked pretty much as expected.

More recently, we noticed that spinning dust also appears in the WIM:

(Dobler & Finkbeiner 2008;
Dobler Draine & Finkbeiner 2008)



T_gas = 8000 K
<μ> = 2.00
X_H = 0.9900
T_gr = 20 K
X_M = 1.0×10^-3
Y = 0.000
χ = 1.0
ν j_ν / n_H^2 [Jy/sr cm^5]
n_H [cm^-3]
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-3
10^-2
10^-1
10^0
10^1
10^2



Full Sky Fit
F+D+C model
free-free
spinning dust
CMB bias
T_{gas} = 4167 K
n_H = 0.05 cm^{-3}
μ_0 = 2 debye
$I_\nu/I_{H\alpha}$ [kJy/sr/R]
0.10
0.01
0.11
0.10
20
40
60
80
100
ν [GHz]

We have seen what looks like Draine & Lazarian spinning dust in both the CNM and the WIM.

The story is somewhat subtle; Greg Dobler can tell you more in December.

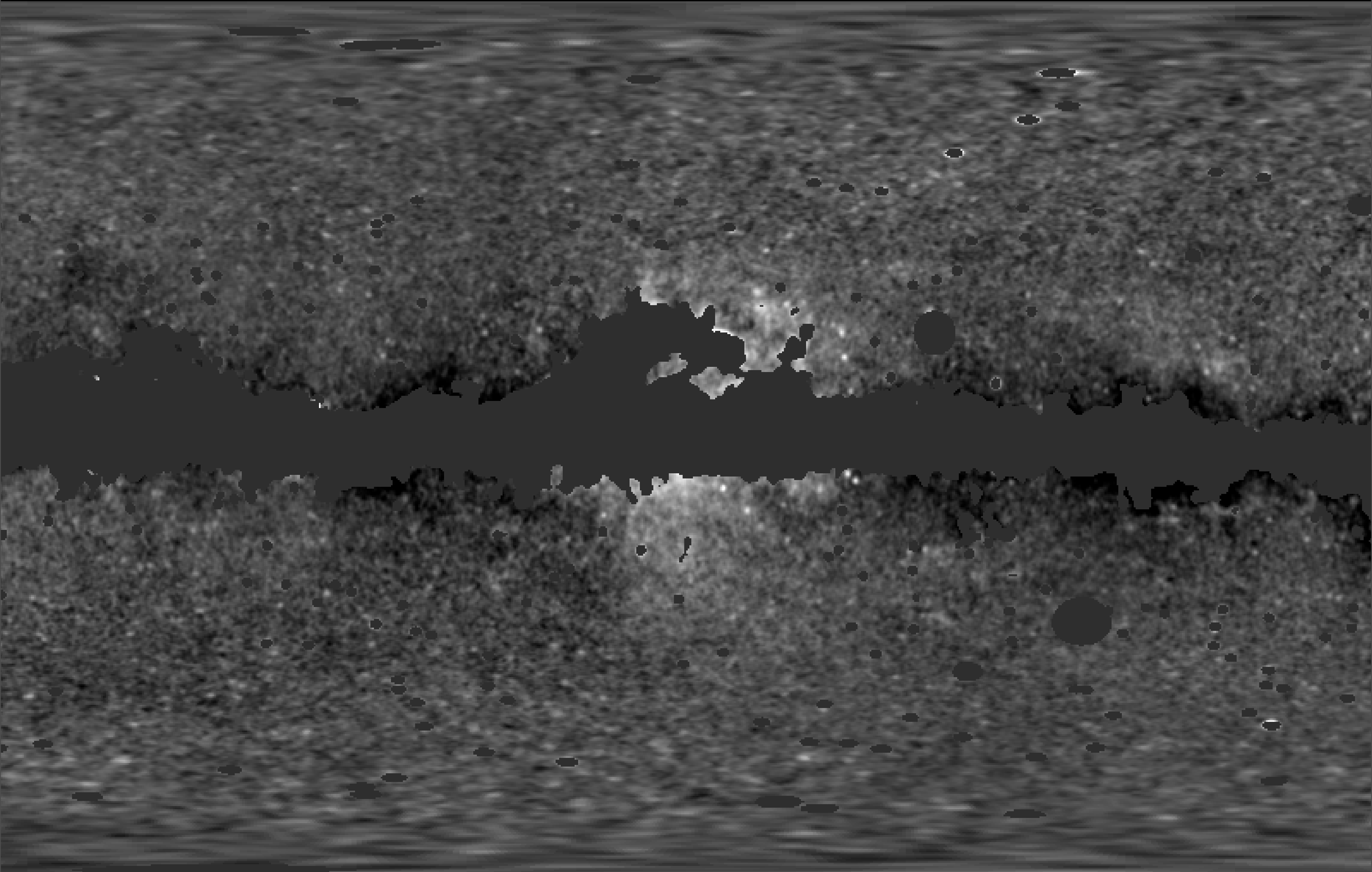
Bottom line: the dust spins, and refined measurements of spinning dust emission in the future may be a useful probe of the conditions in the ISM.

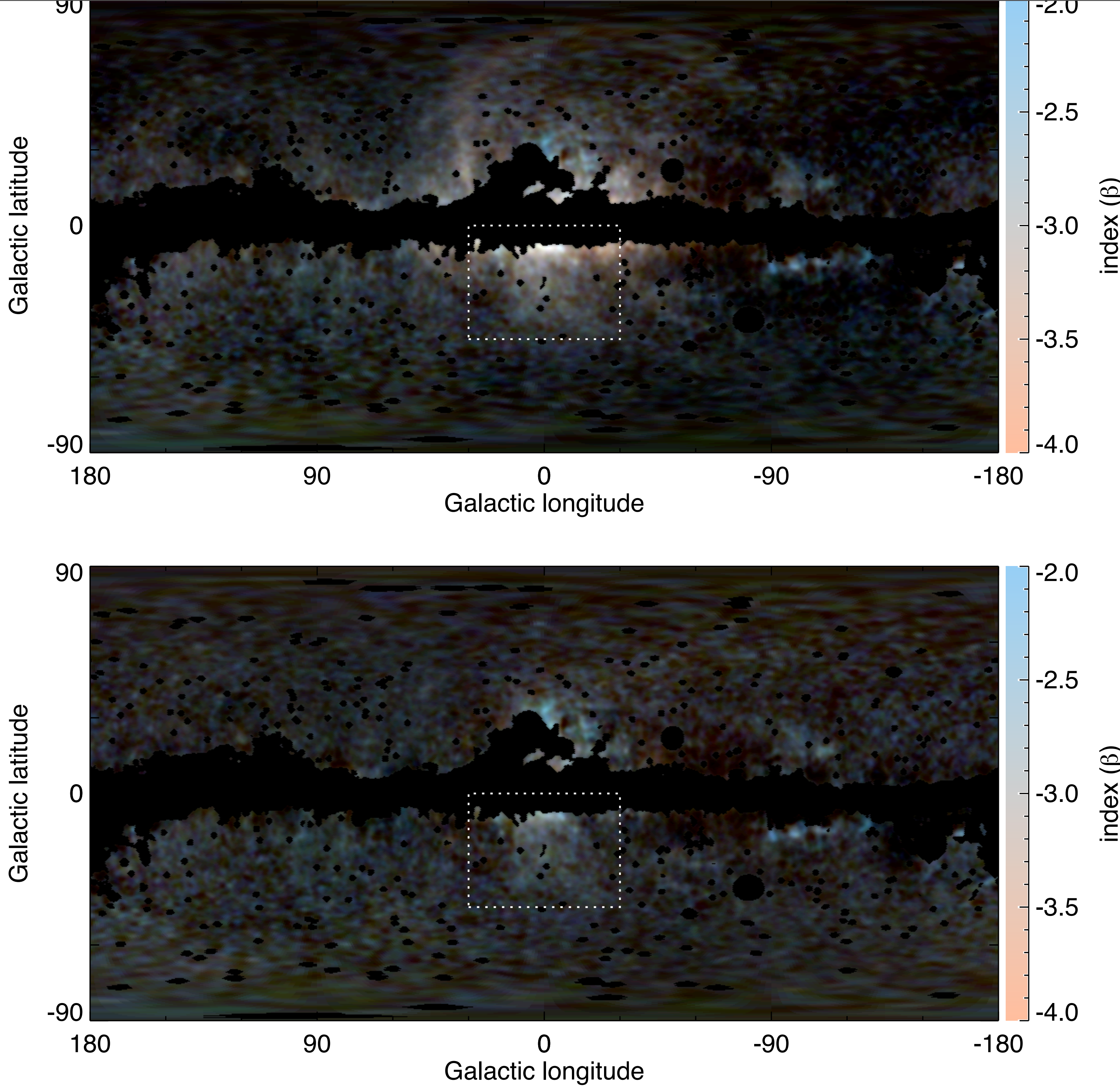
Galactic emission over most of the sky is well modeled by those 4 components.

In the inner Galaxy (inner 25 deg / few kpc) there is an additional microwave component that is spatially different from the other 4.

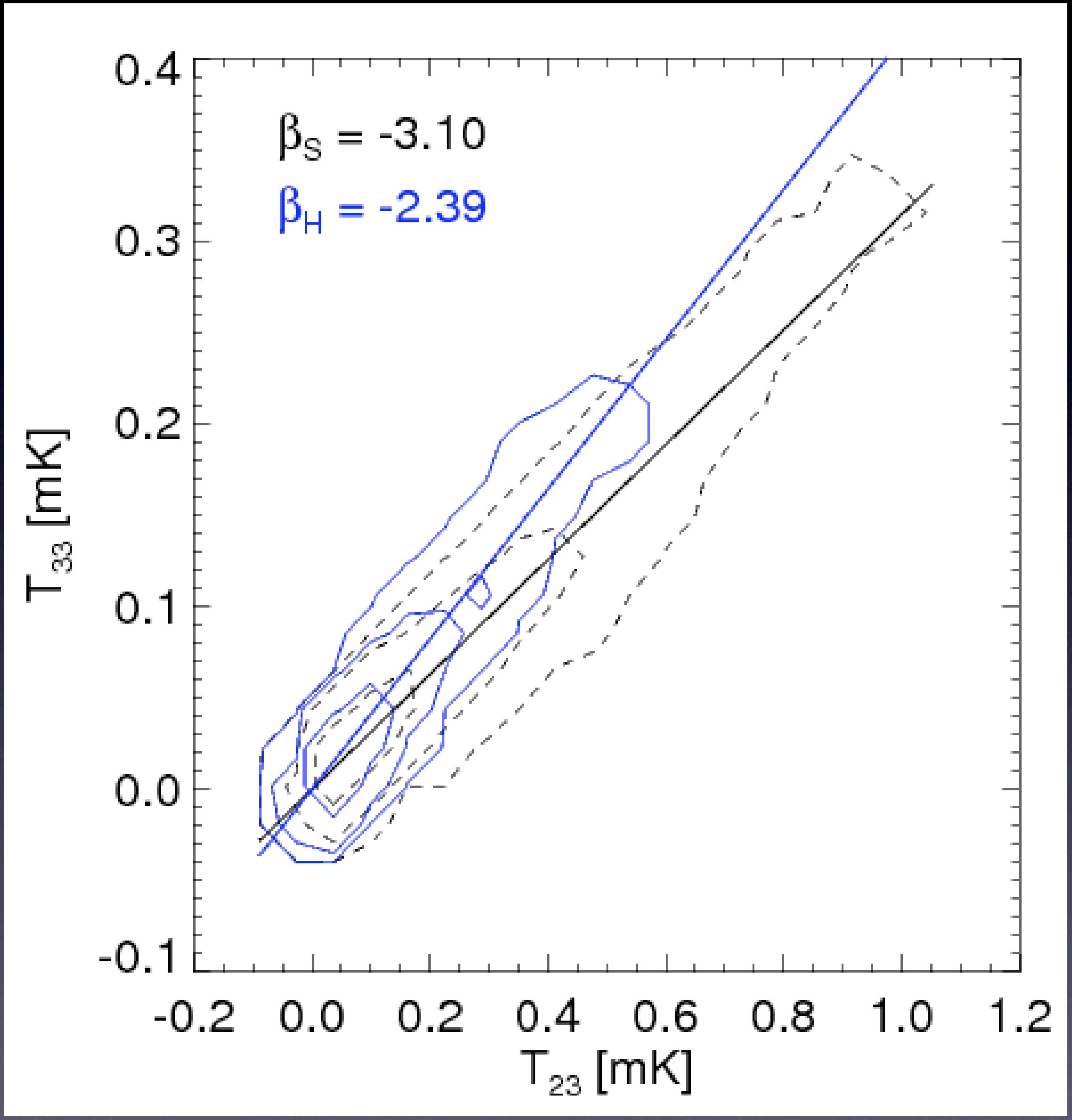
We call this the "Galactic Haze" because of its smooth appearance.

(Finkbeiner 2004;
Hooper, Dobler, Finkbeiner 2007)

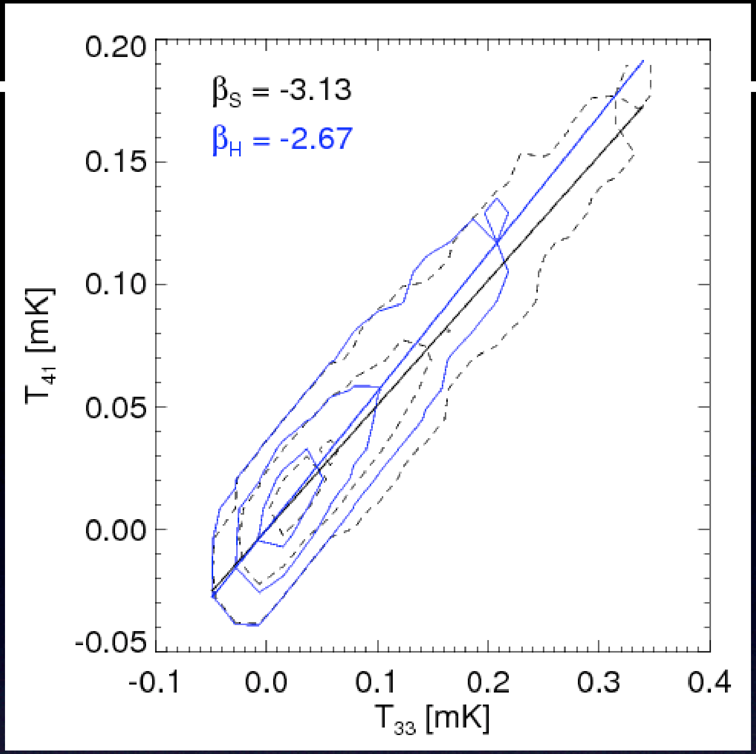




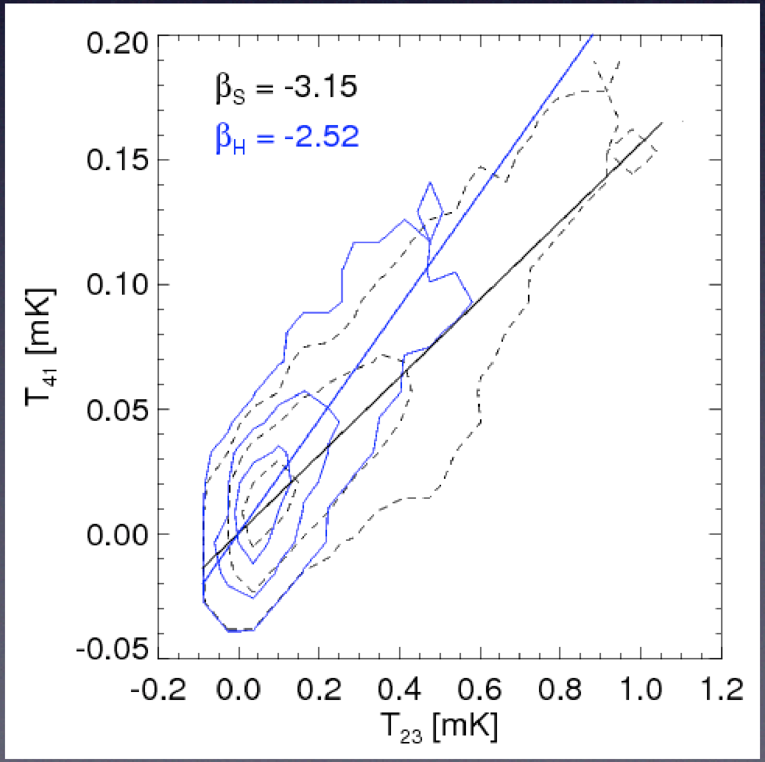
Galactic latitude
90
0
-90
180
90
0
-90
-180
Galactic longitude
index (β)
-2.0
-2.5
-3.0
-3.5
-4.0
Galactic latitude
90
0
-90
180
90
0
-90
-180
Galactic longitude
index (β)
-2.0
-2.5
-3.0
-3.5
-4.0



β_S = -3.10
β_H = -2.39
T_{33} [mK]
T_{23} [mK]



β_S = -3.13
β_H = -2.67
T_{41} [mK]
T_{33} [mK]



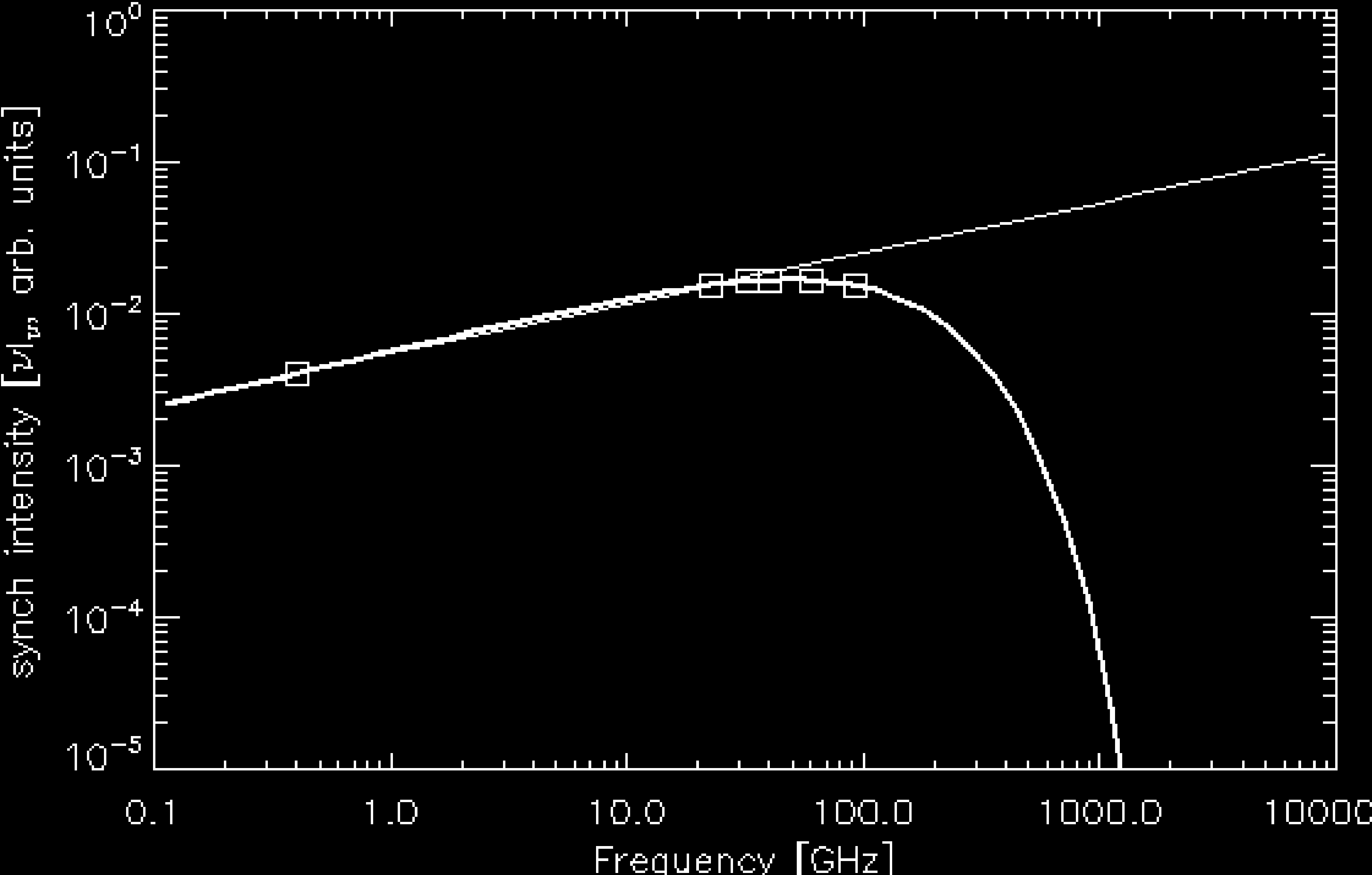
β_S = -3.15
β_H = -2.52
T_{41} [mK]
T_{23} [mK]

Why model the haze as a separate component?

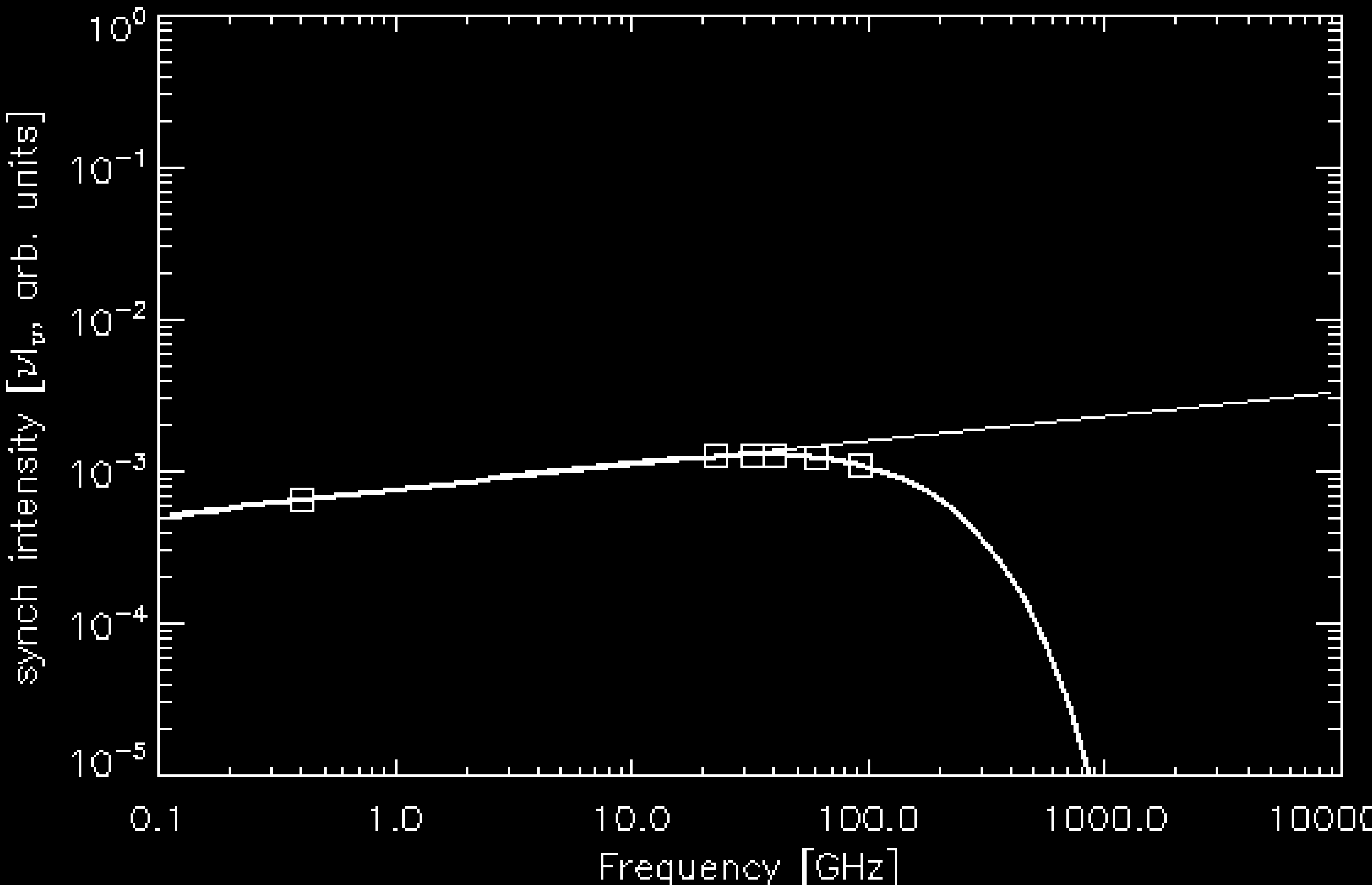
It appears to have a “concave - up” spectrum. Synchrotron from SN shocks should not (in general) do that.

As an illustration, we computed synchrotron from 2000 SNe in the inner few kpc, with usual diffusion and energy loss terms:

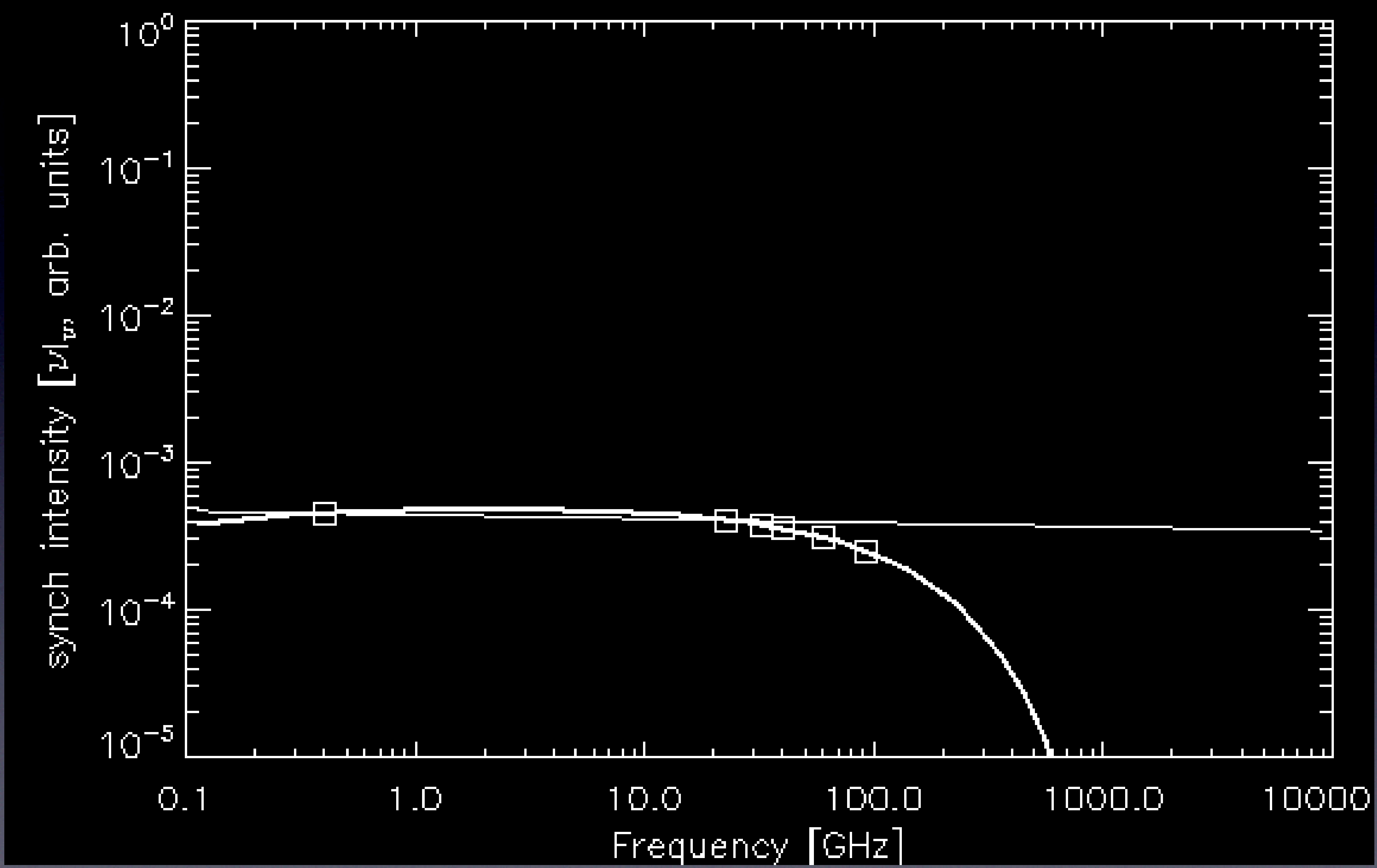
(Dobler & Finkbeiner 200[8|9])



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
synch intensity [νI_ν arb. units]
0.1
1.0
10.0
100.0
1000.0
10000
Frequency [GHz]



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
synch intensity [νI_ν, arb. units]
0.1
1.0
10.0
100.0
1000.0
10000
Frequency [GHz]

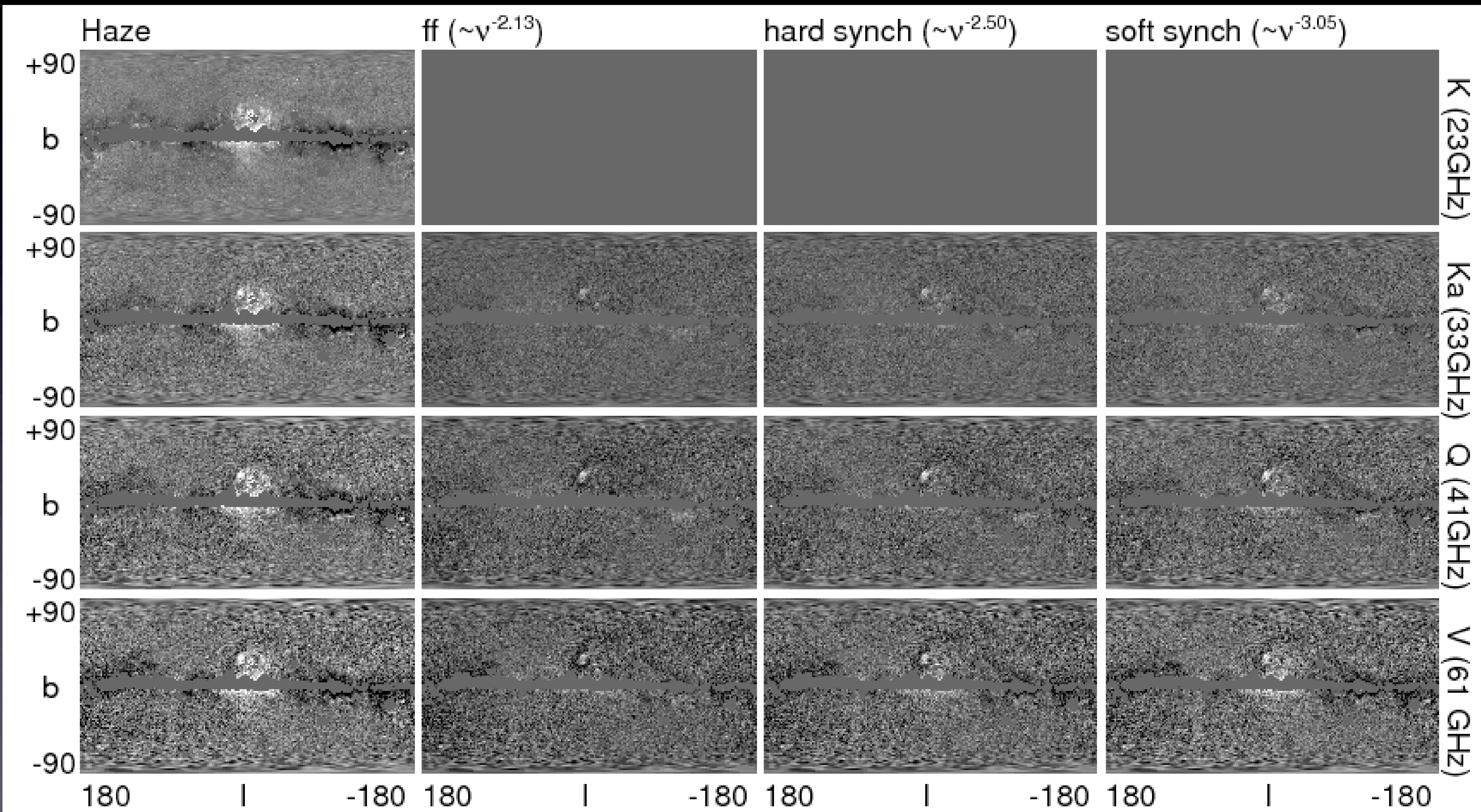


synch intensity [νI_ν, arb. units]
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
0.1
1.0
10.0
100.0
1000.0
10000
Frequency [GHz]

Conclusions from that exercise:

1. A power law is not a good description of synchrotron at high frequencies

2. The spectrum should get steeper (softer) at higher frequencies.


Haze
ff (~$\nu^{-2.13}$)
hard synch (~$\nu^{-2.50}$)
soft synch (~$\nu^{-3.05}$)
+90
b
-90
K (23GHz)
Ka (33GHz)
Q (41GHz)
V (61 GHz)
180
l
-180

The synchrotron spectrum in the inner MW appears to be concave up.

This implies another separate source of electrons (other than SN shocks) with a harder spectrum.

Because the cooling time is fast (500,000 yr) the source must be spatially distributed.

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Yes, but more SNe -> more synch, not harder

3. Is it diffusion hardening / Gal winds?
Everett et al. (2008) estimate 5×10^{6}yr for CR escape, but cooling time is 5×10^{5}yr.

Nevertheless, all these statements would be more precise with better data.

The CMB Cross-correlation bias is the dominant concern.

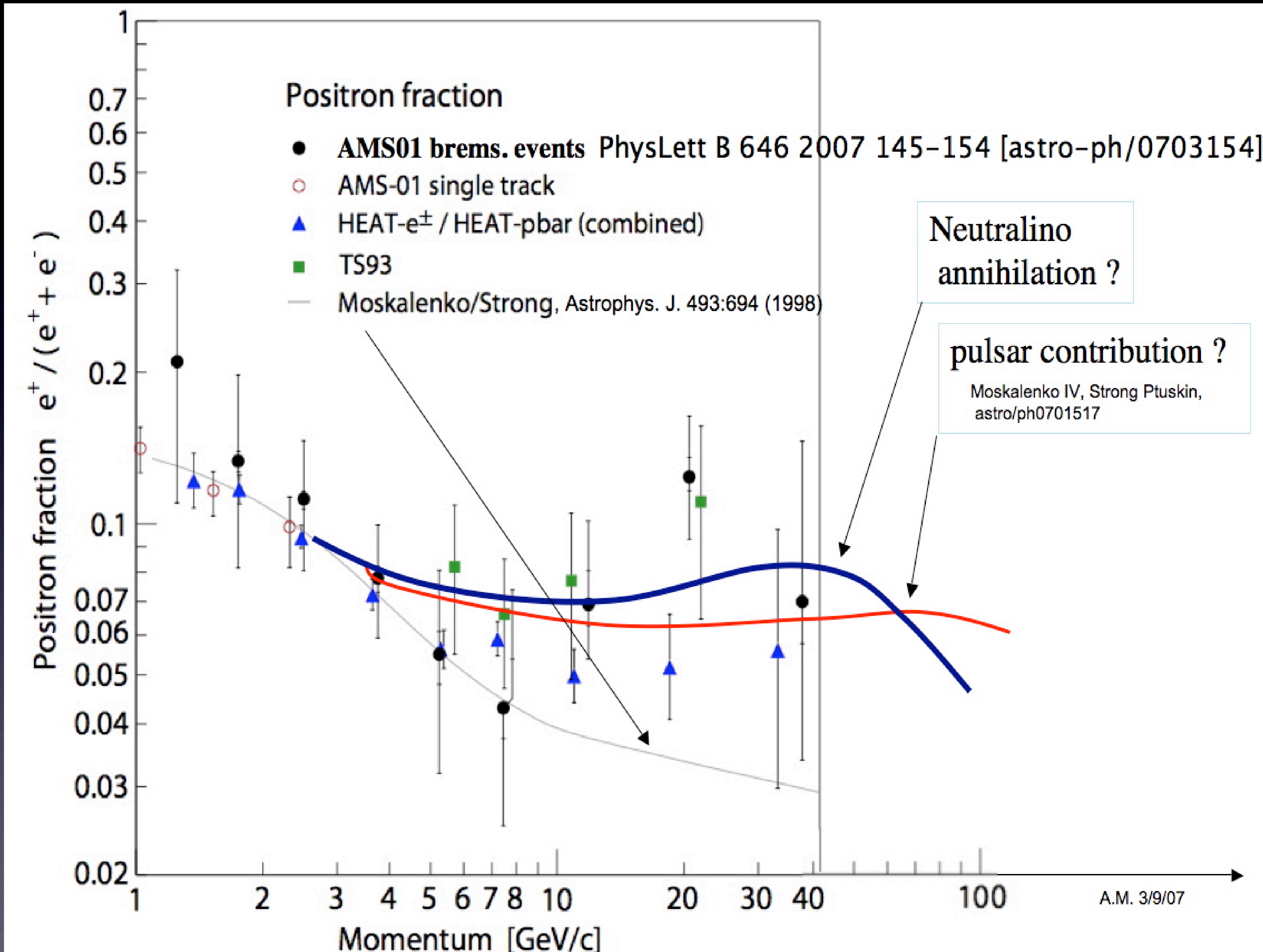
(Any one realization of the true CMB has correlations with the true foregrounds, even though the "average Universe" does not)

The superior frequency coverage of Planck mostly breaks these degeneracies, measuring the haze spectrum a factor of 10 better.
(Dobler & Finkbeiner 2008)

Why is this so important to get the haze right?

Are there other indications of WIMP annihilation?

The HEAT positron excess



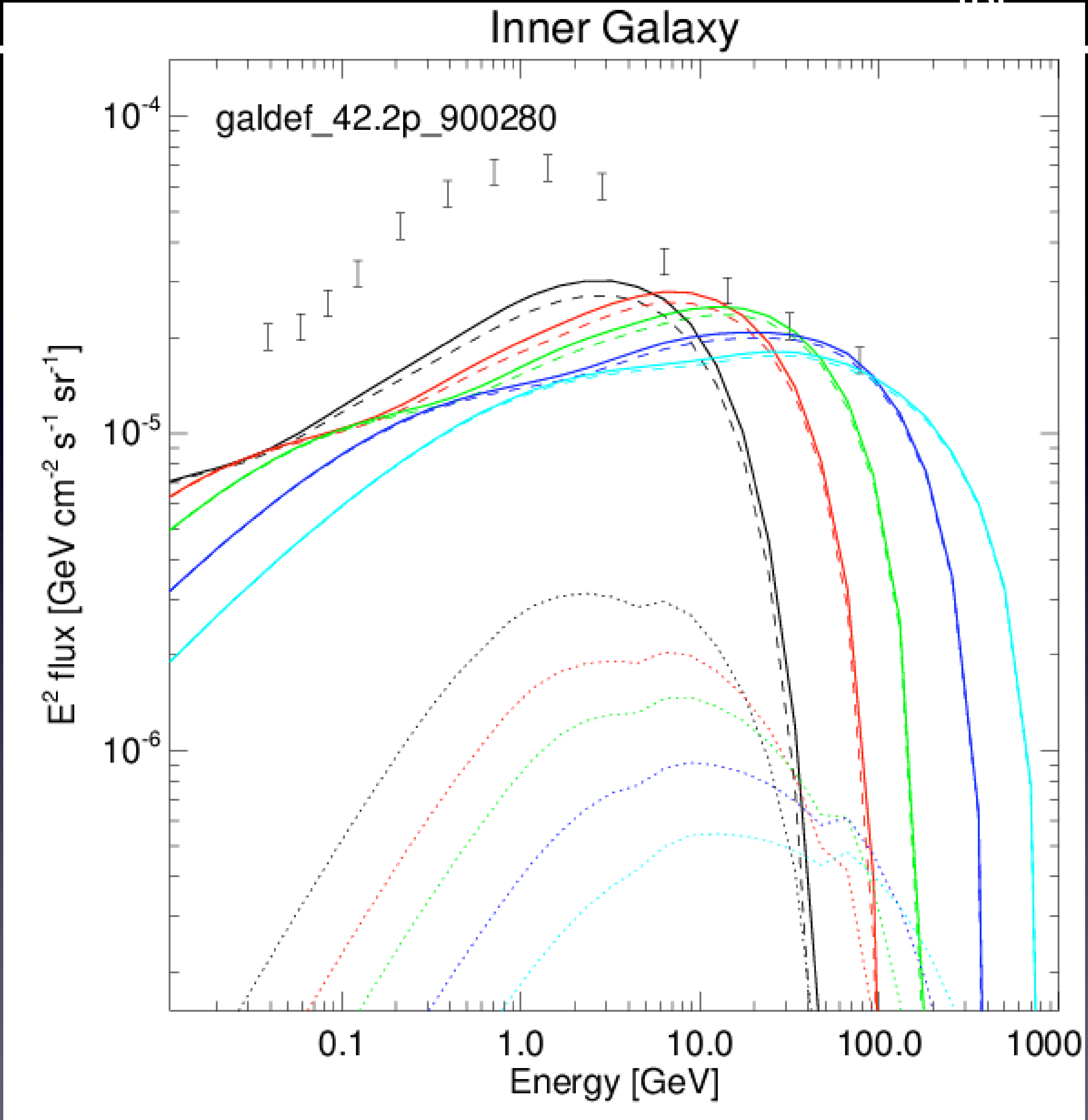
Positron fraction
AMS01 brems. events PhysLett B 646 2007 145-154 [astro-ph/0703154]
AMS-01 single track
HEAT-e± / HEAT-pbar (combined)
TS93
Moskalenko/Strong, Astrophys. J. 493:694 (1998)
Neutralino annihilation ?
pulsar contribution ?
Moskalenko IV, Strong Ptuskin, astro/ph0701517
Positron fraction e+/(e+ + e-)
Momentum [GeV/c]
A.M. 3/9/07

It is often said you need a “boost” of 10-50 to explain HEAT, etc.

However, if you go straight to muons, save factor of 3.
XDM gives 2 phis for 2 chis - factor 2.
positrons come out in just right energy range - factor of few.

You could also get a big Sommerfeld enhancement (more on that later)

The EGRET excess



Inner Galaxy
galdef_42.2p_900280
10^{-4}
10^{-5}
10^{-6}
E² flux [GeV cm⁻² s⁻¹ sr⁻¹]
0.1
1.0
10.0
100.0
1000
Energy [GeV]

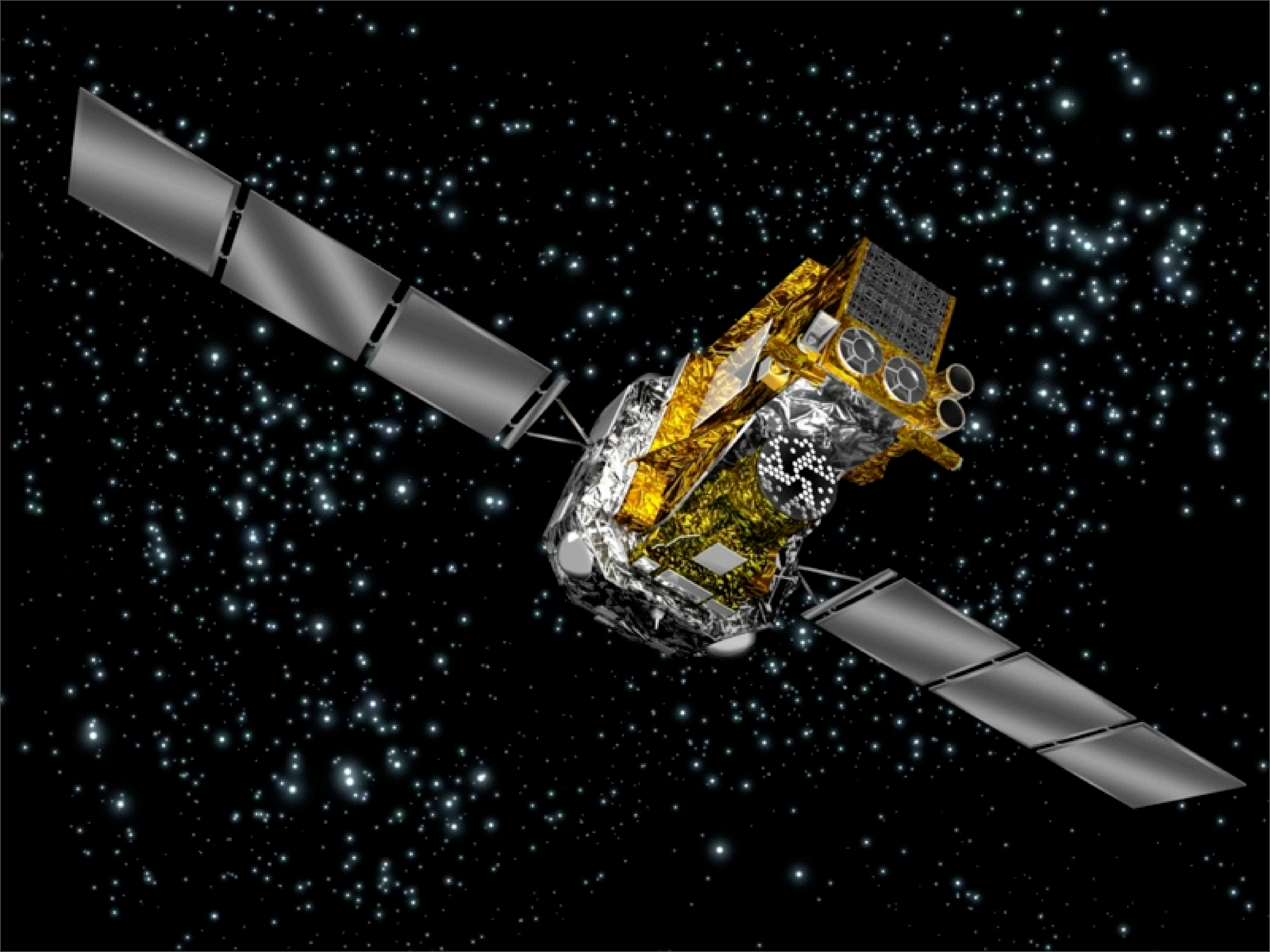
The INTEGRAL 511 keV excess

Let's consider the 511 keV line / continuum from positron annihilation, observed by many balloon and satellite experiments, most recently CGRO/OSSE and INTEGRAL / SPI (Weidenspointner et al., Knoedlseder et al. ...)

The unexplained excess is roughly a 6 deg FWHM Gaussian with a total of
3×10^{42} pairs/s = 3×10^{39} GeV/s = 5×10^{36} erg/s

Integral / SPI: (spectrometer)

- Energy range: 20 keV - 8 MeV
- Detector area: 500 cm^2
- Field of view: 16 deg (fully coded)
- Angular resolution: 2.5 deg FWHM
- Launched: 2002 Oct 17
- Still operating...

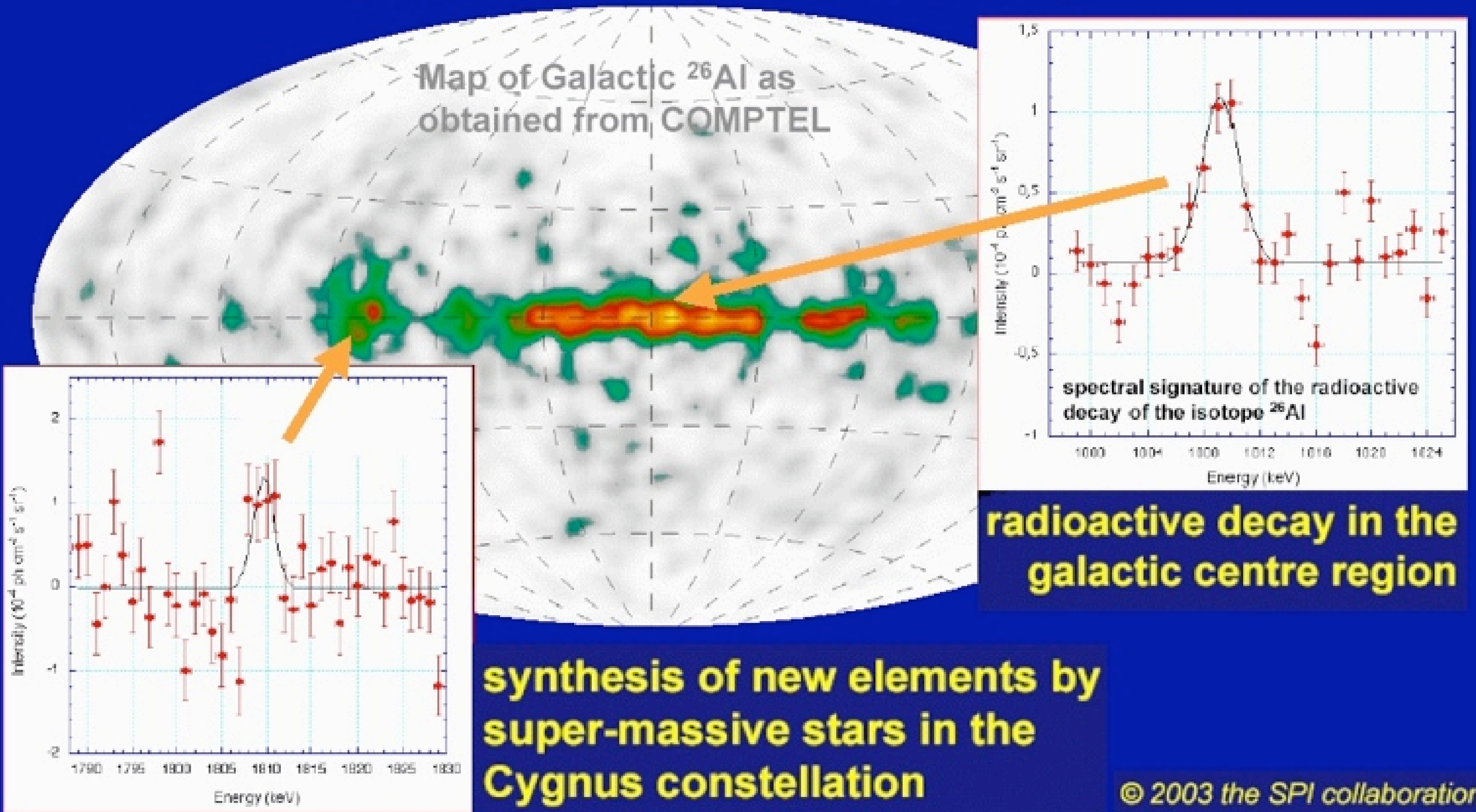


With this spectrograph, one can look at the 1.8 MeV ^{26}Al line, the 511 keV e^+e^- line, etc.

^{26}Al traces massive star formation (i.e. SNe) half life is ~ 10^6 years.

Radioactive ^{26}Al in the Galaxy

- first results from SPI/INTEGRAL -



- Most (92+-8%) of the positrons form positronium (Ps, an e^+e^- atom) before annihilating. (Weidenspointner 2006,2007)

- 3/4 are ortho-Ps and annihilate to 3 photons
- 1/4 annihilate to 2 photons (511 keV line)

Weidenspointner (2006)

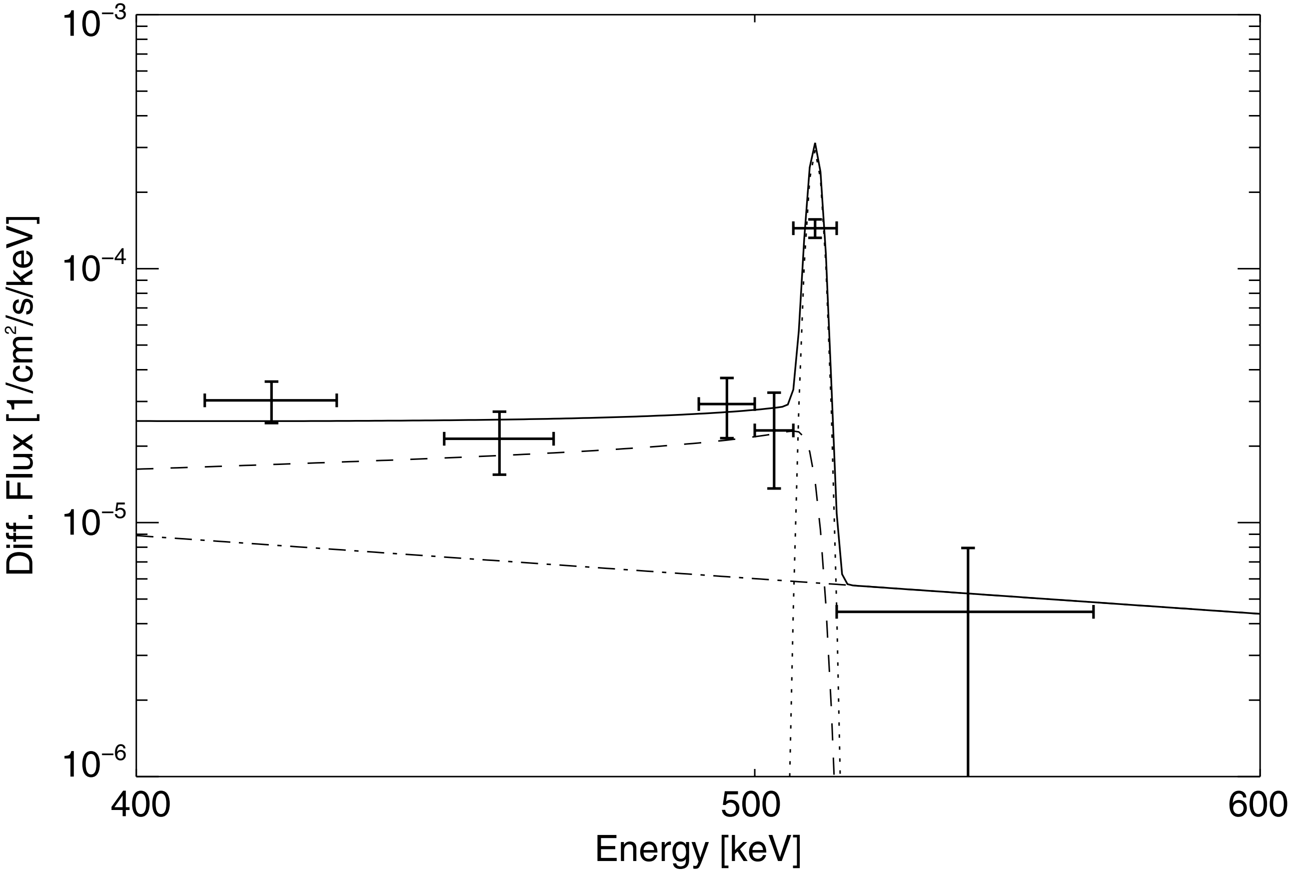


Fig. 2. A fit of the SPI result for the diffuse emission from the GC region ($|l|, |b| \leq 16^{\circ}$) obtained with a spatial model consisting of an 8° *FWHM* Gaussian bulge and a CO disk. In the fit a diagonal response was assumed. The spectral components are: 511 keV line (dotted), Ps continuum (dashes), and power-law continuum (dash-dots). The summed models are indicated by the solid line. Details of the fitting procedure are given in the text.

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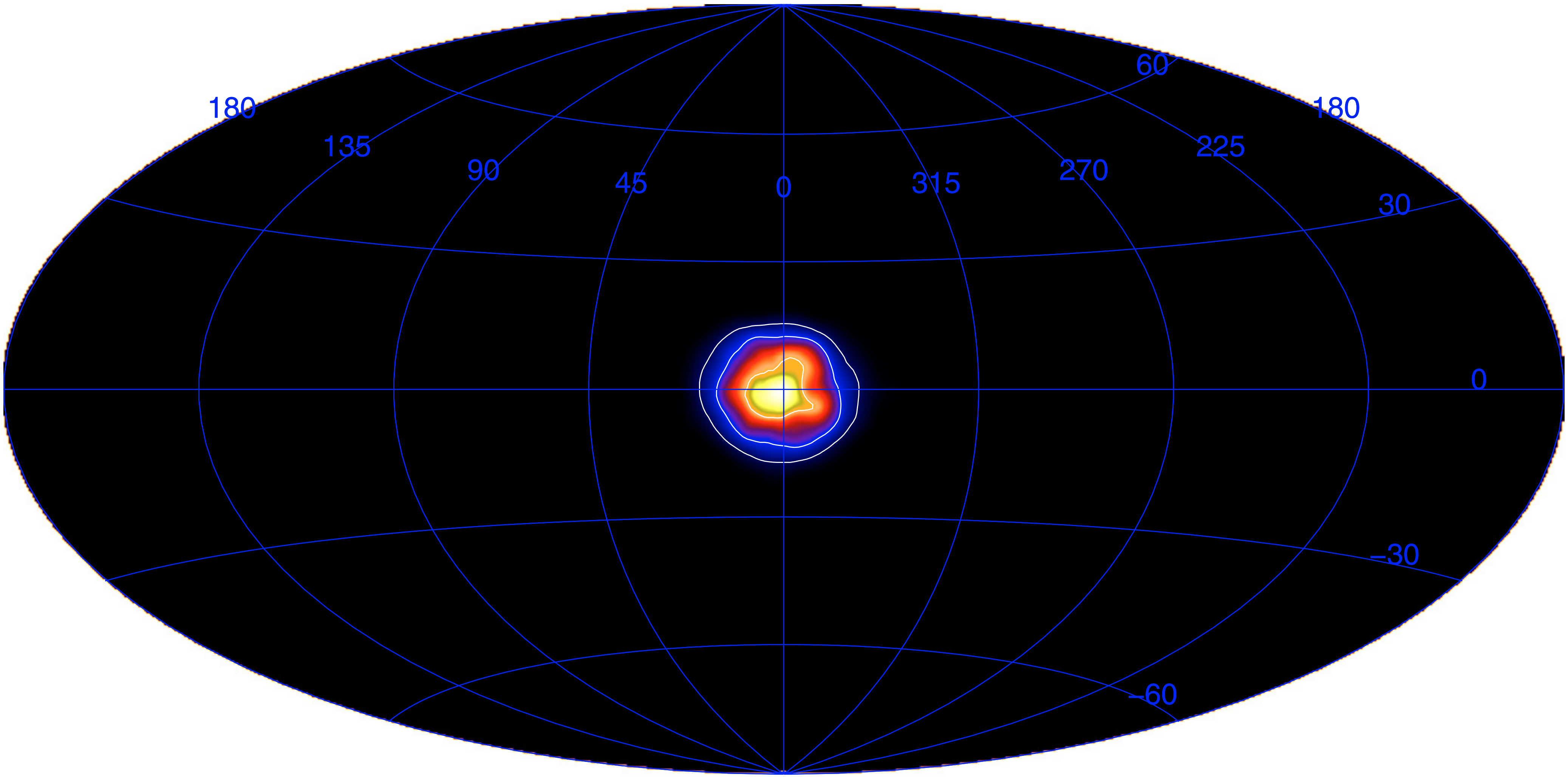
(2006)

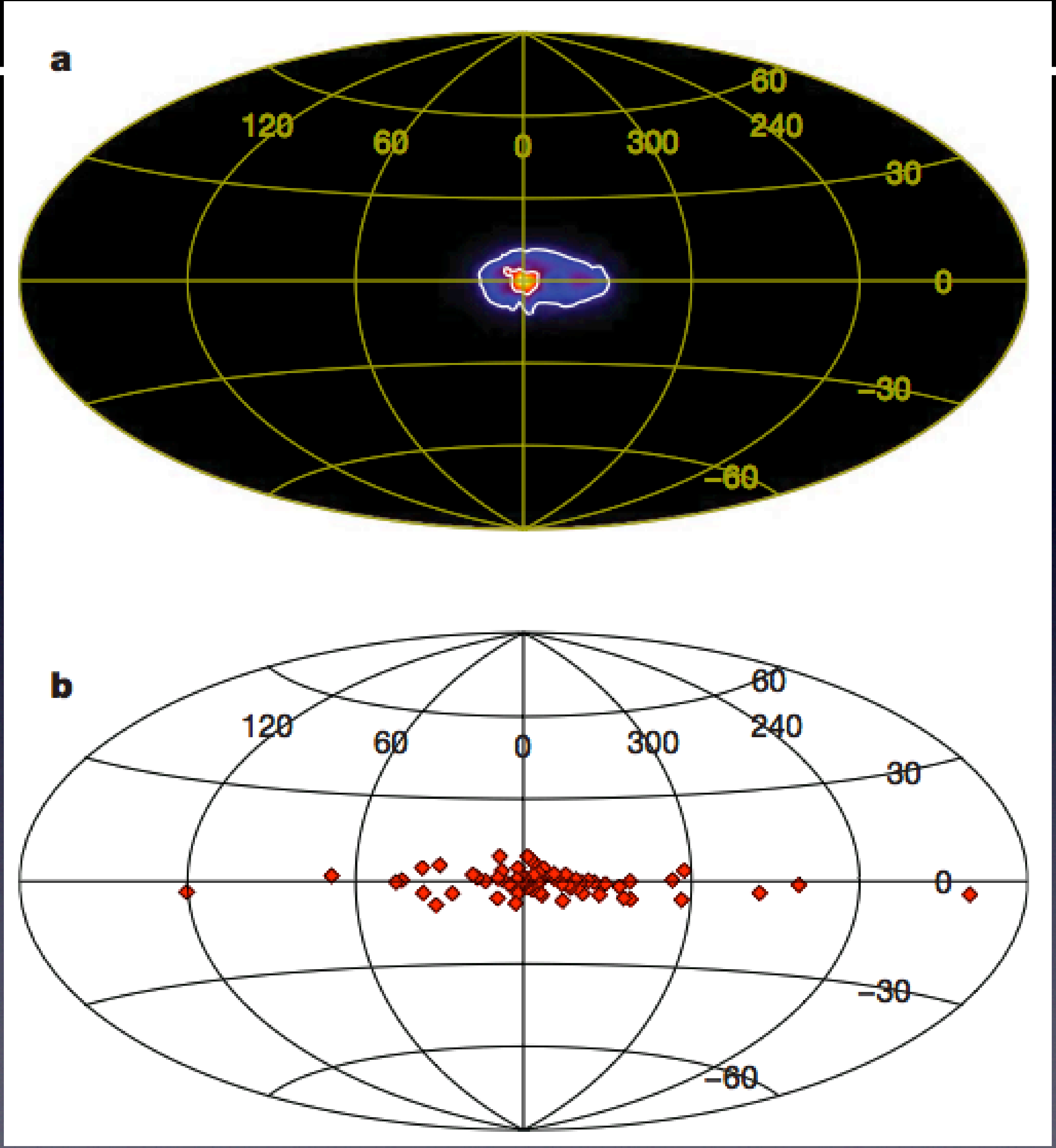
G. Weidenspointner et al.: The sky distribution of positronium continuum emission



- The positronium signal is centrally concentrated.
- There is a disk component, but much fainter.
- The disk component is roughly what we expect from SNe Ia; the bulge component is 10 times brighter than expected.

- Kalemci et al (2006) find positron escape fraction is too low anyway.

- There is a recent suggestion that LMXBs could do it (Low-mass X-ray binaries)



Weidenspointner et al. (2008)   Integral signal (top) and LMXBs (bottom)

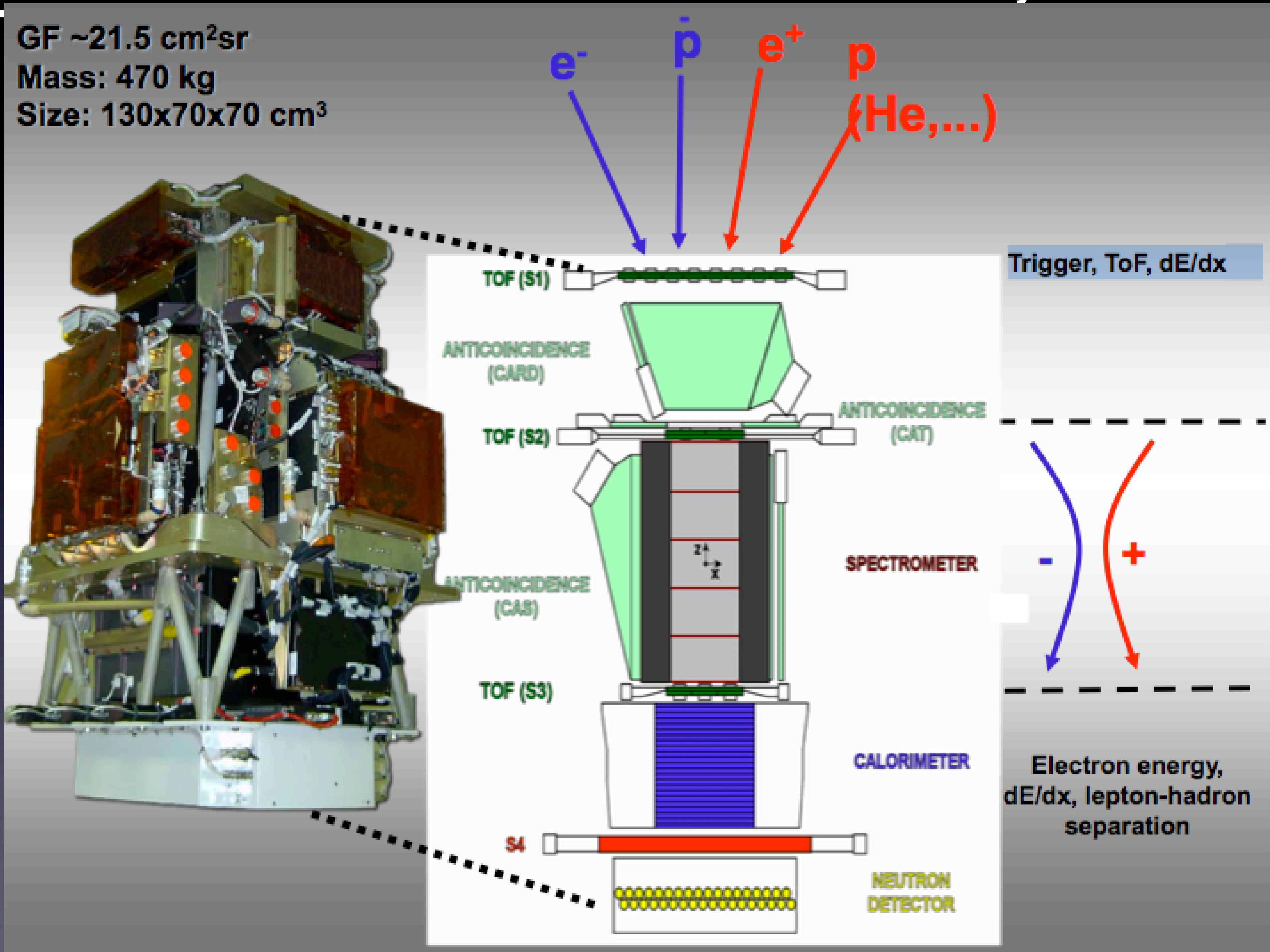
There is a lot of evidence for electronic activity from HEAT, EGRET, WMAP, and INTEGRAL.

Recently the HEAT result has been improved greatly by PAMELA...

PaMeLa

a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

PAMELA data have not been released, so we must rely on the astro-paparazzi...

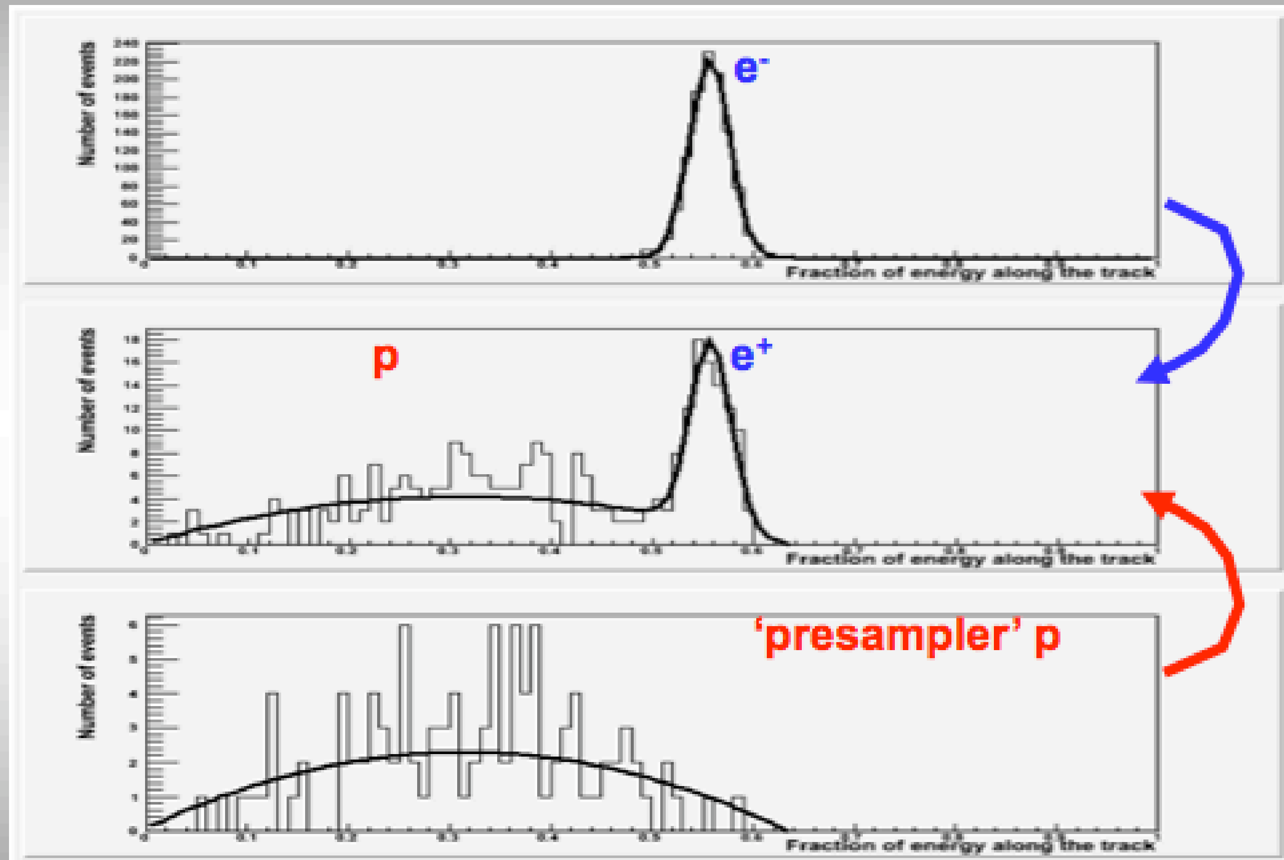


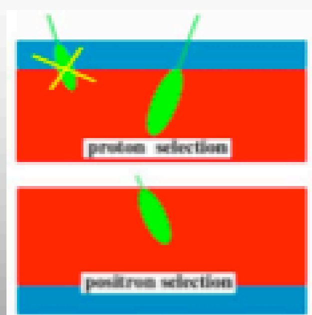
Courtesy Mirko Boezio

e^+ background estimation from data

Rigidity: 20-30 GV

Preliminary





Fraction of charge released along the calorimeter track (left, hit, right)

+
- Energy-momentum match
- Starting point of shower

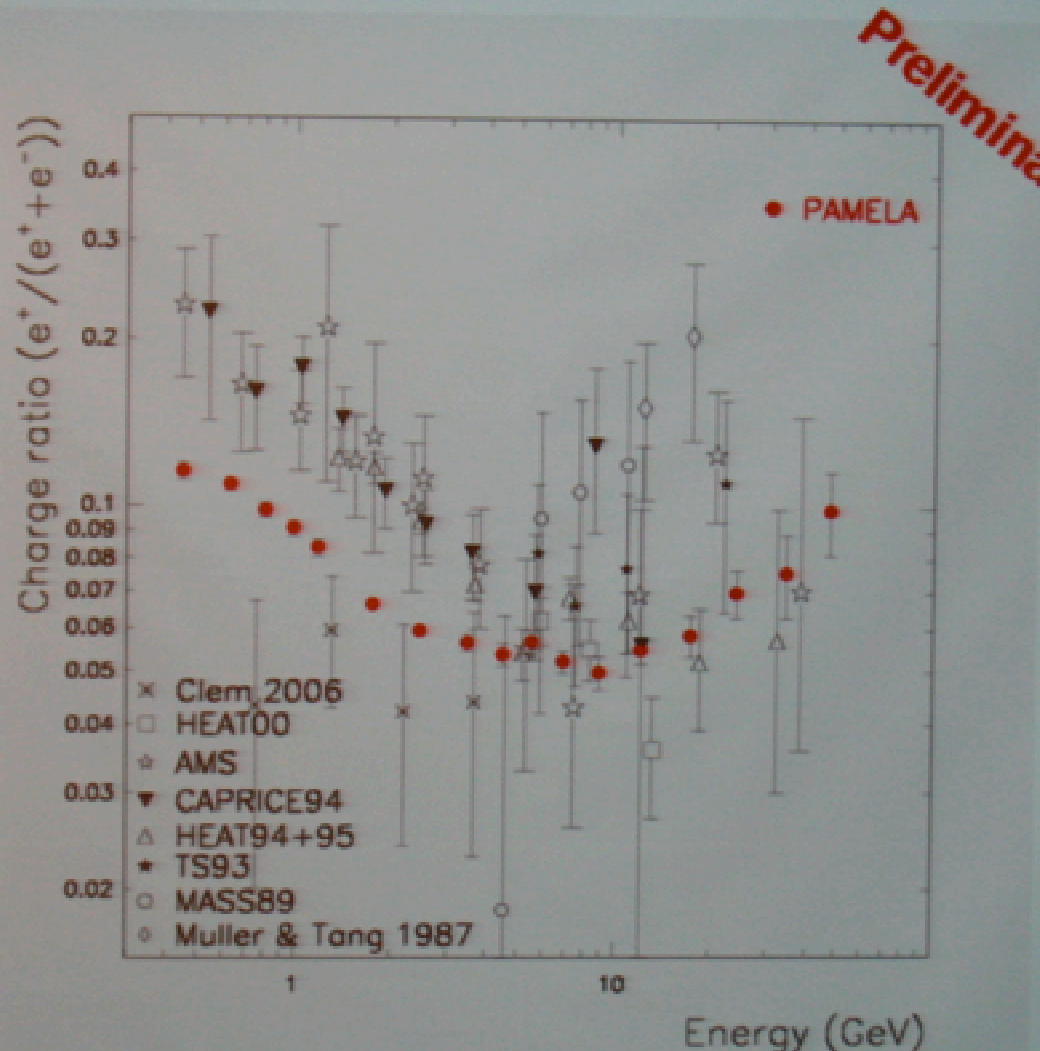
Mirko Boezio, INFN Trieste - ICHEP08, 2008/08/01

Courtesy Mirko Boezio

PAMELA data have not been released, so we must rely on the astro-paparazzi...

Positron to Electron Fraction

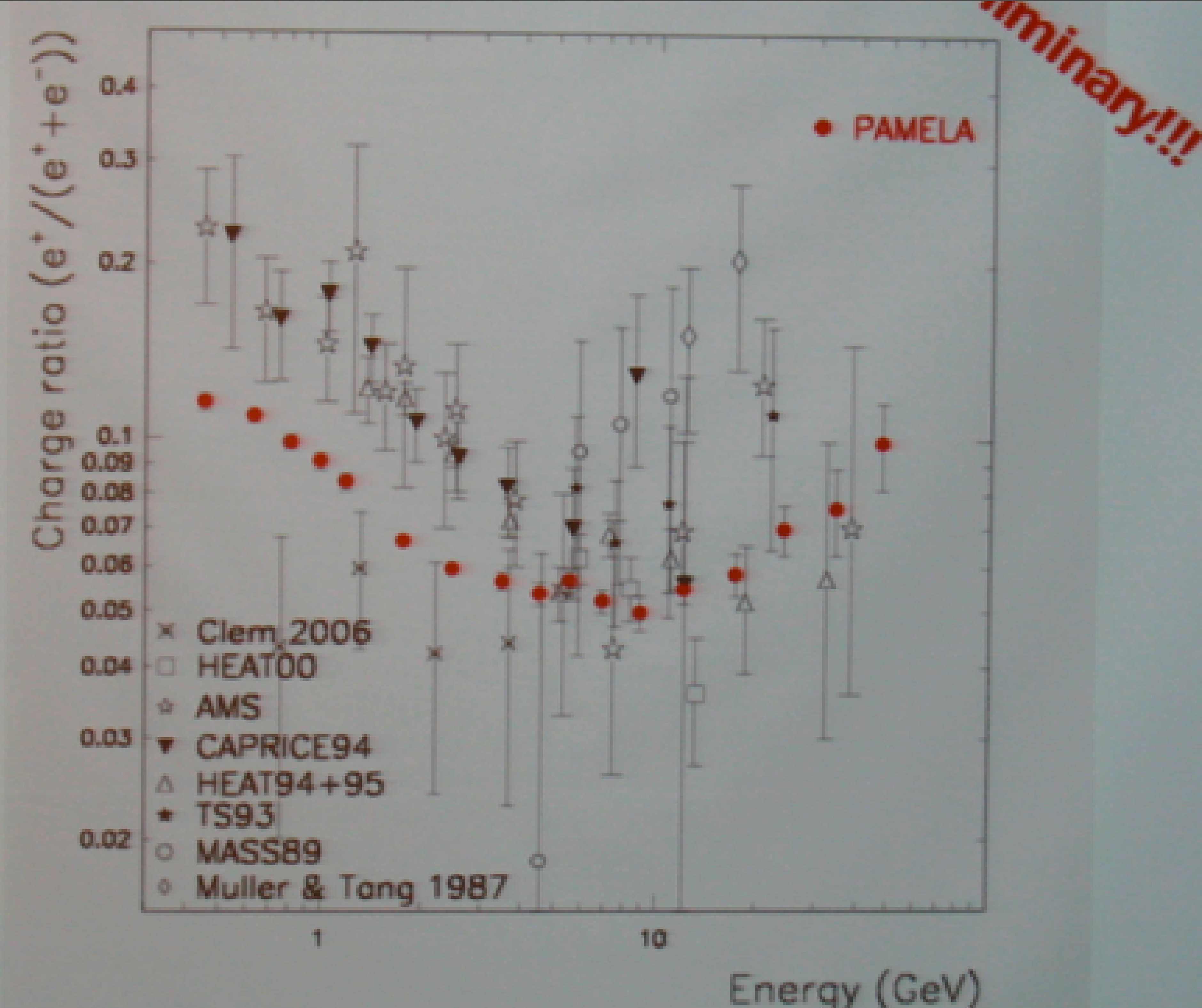
Preliminary!!!



End 2007:
~20 000
positrons total

~2000 > 5 GeV

Mirko Boezio, IDM2008, 2008/08/20



liminary!!!
PAMELA
Charge ratio (e⁺/(e⁺+e⁻))
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
Clem 2006
HEAT00
AMS
CAPRICE94
HEAT94+95
TS93
MASS89
Muller & Tang 1987
1
10
Energy (GeV)

The HEAT signal as been tantalizing for several years, but with PAMELA the rise in the positron fraction is now *very* pronounced.

This is a serious challenge to most production mechanisms, even pair production cascades in pulsars...

If we want to figure out what is going on, we should start at the highest energy scale and work down...

The highest energy scale would be... ATIC!

ATIC = Advanced Thin Ionization Calorimeter
Preliminary data from 2005:

29th International Cosmic Ray Conference Pune (2005) **00**, 101–104

The Electron Spectrum above 20 GeV Measured by ATIC-2

J. Chang[a], W.K.H. Schmidt[b], J.H. Adams[e], H.S. Ahn[d], G. Bashindzhagyan[g], K.E. Batkov[g], M. Christl[c], A.R. Fazely[f], O. Ganel[d], R. M. Gunasingha[f], T.G. Guzik[c], J. Isbert[c], K.C. Kim[d], E. Kouznetsov[g], M. Panasyuk[g], A. Panov[g], E.S. Seo[d], N. Sokolskaya[g], J.Z. Wang[d], J.P. Wefel[c], J. Wu[d], V. Zatsepin[g]

ATIC = Advanced Thin Ionization Calorimeter
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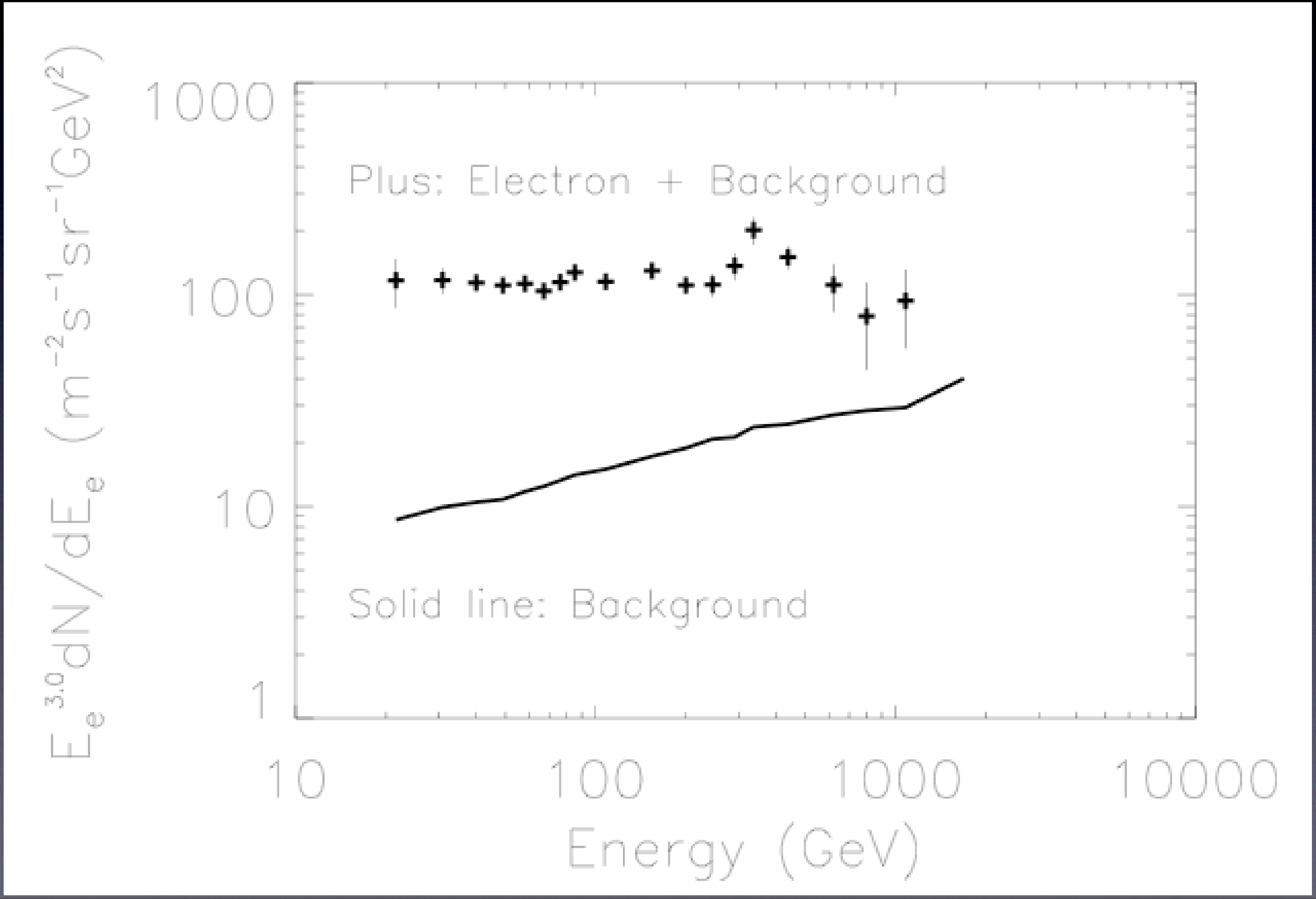
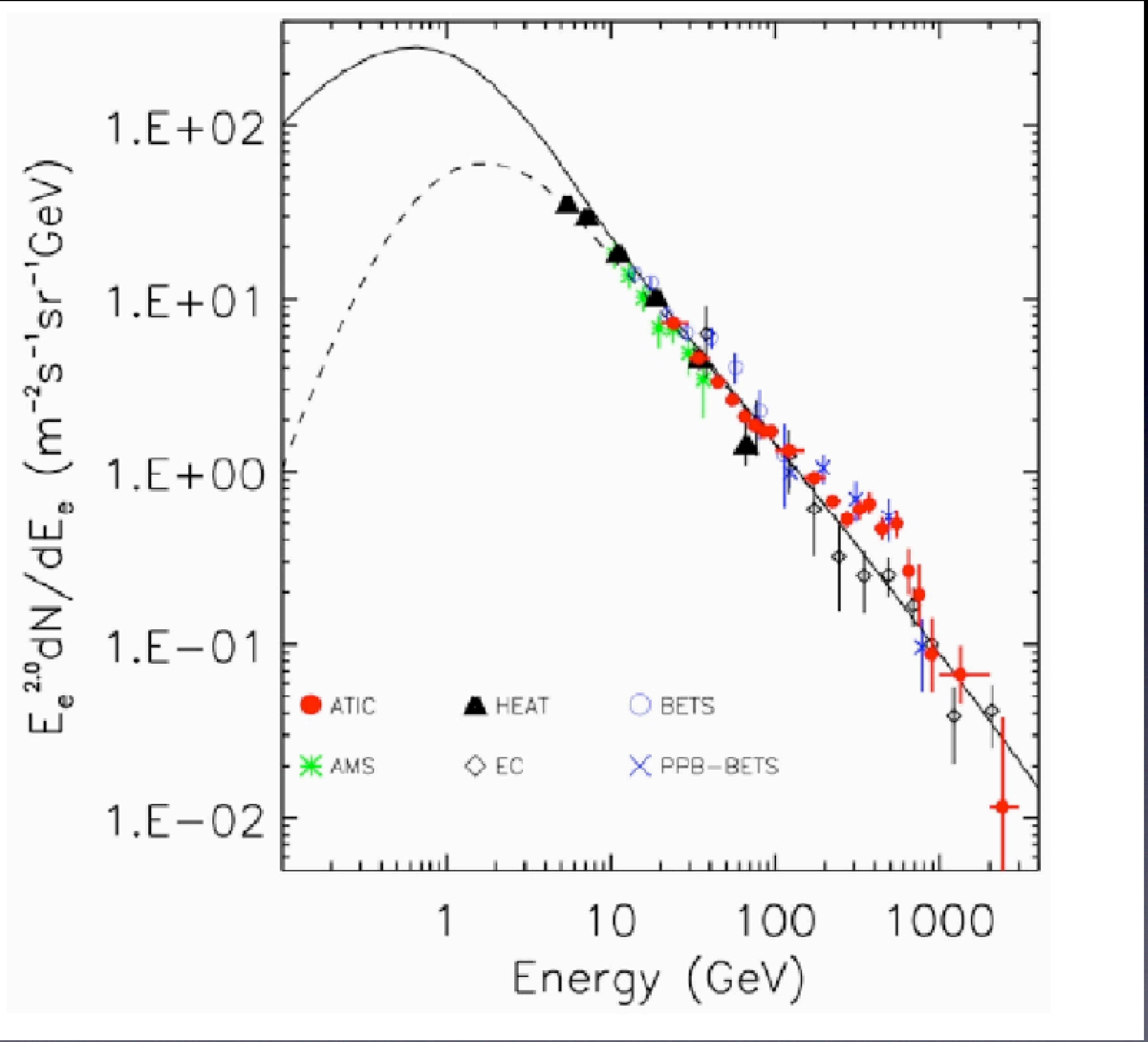


ATIC = Advanced Thin Ionization Calorimeter
Preliminary data from 2005:
There is a bump at several hundred GeV !!



1.E+02
1.E+01
1.E+00
1.E−01
1.E−02
$E_e^{2.0} dN/dE_e$ ($m^{-2}s^{-1}sr^{-1}GeV$)
1
10
100
1000
Energy (GeV)
ATIC
HEAT
BETS
AMS
EC
PPB−BETS

Suppose we take the bump seriously and attempt to explain it with a WIMP.

The WIMP mass must be in the ~ 800 GeV range.

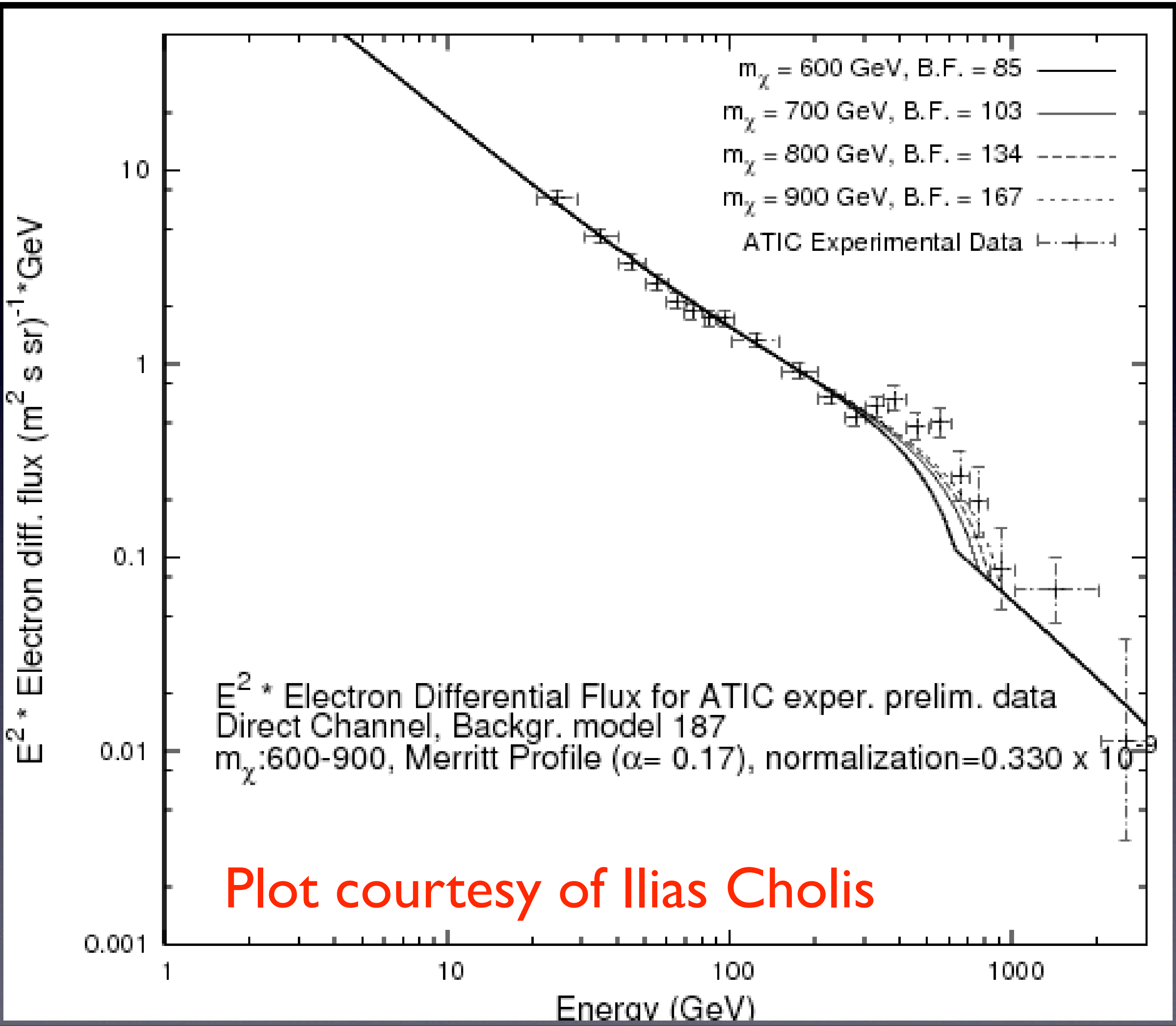
A WIMP must produce equal numbers of e^+ and e^-

PAMELA constraint is critical!

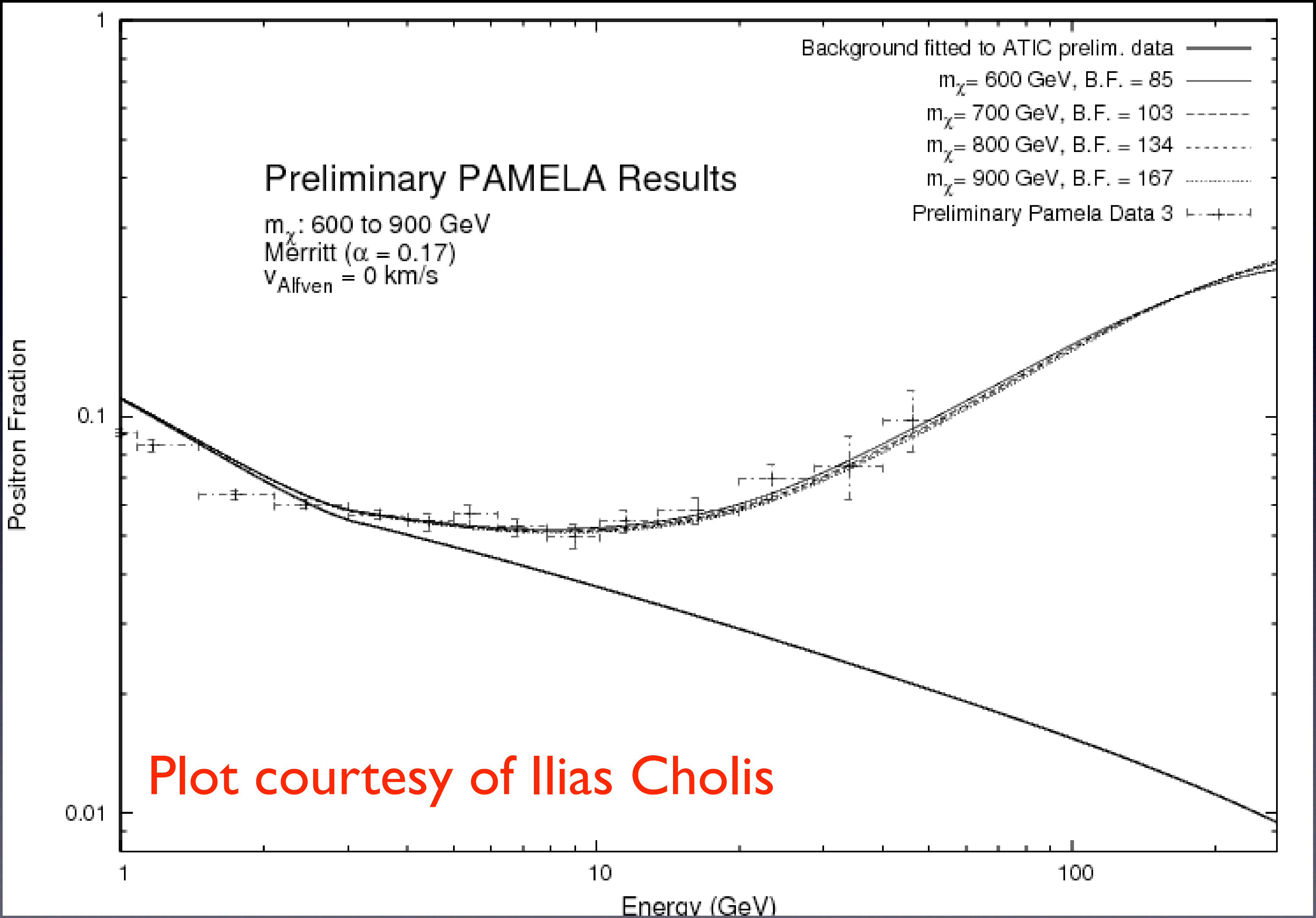
Toy model:

~800 GeV WIMP, goes directly or indirectly to SM particles. What cross section do we need for ATIC?

What does this give for PAMELA?



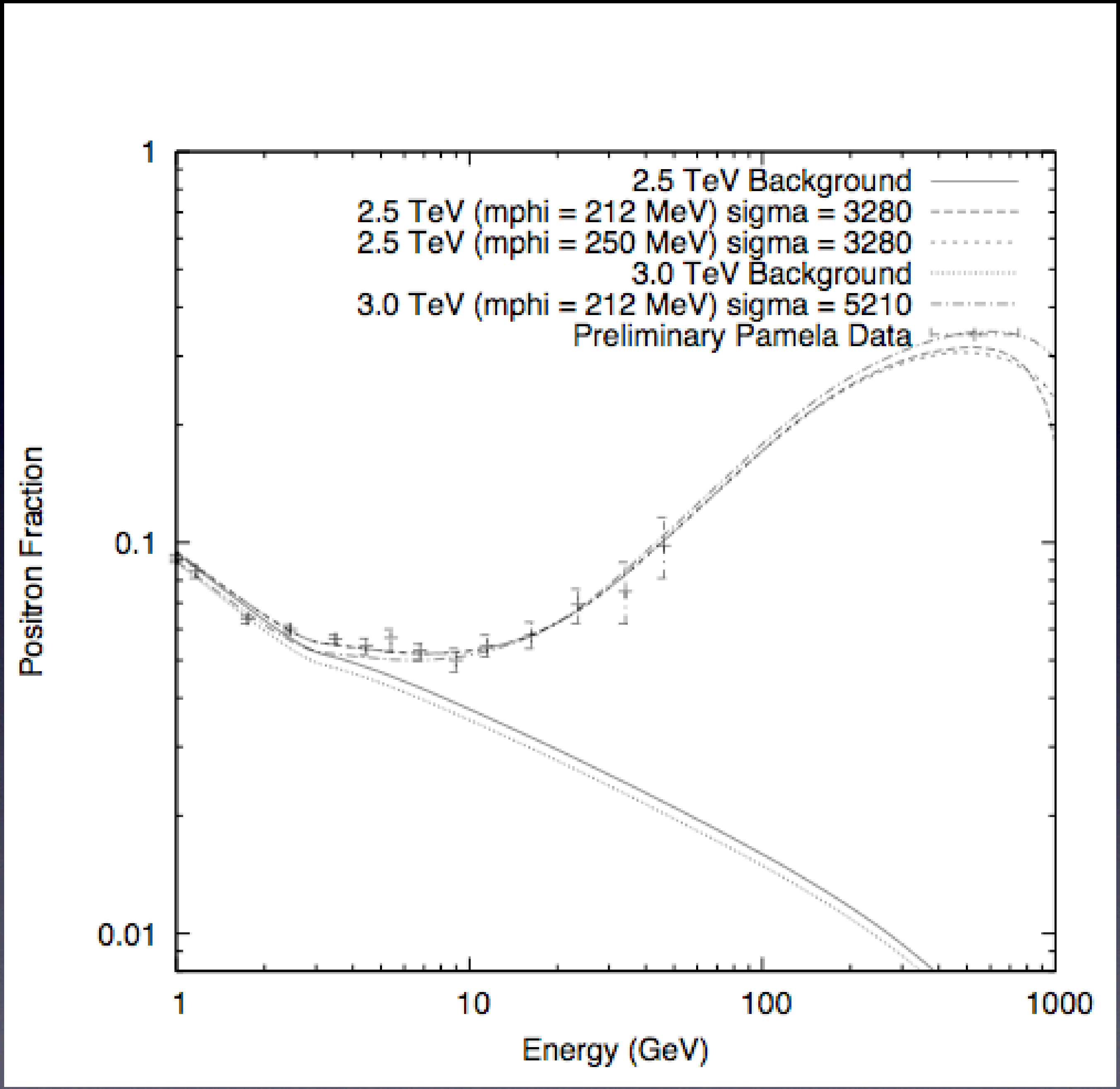
Plot courtesy of Ilias Cholis



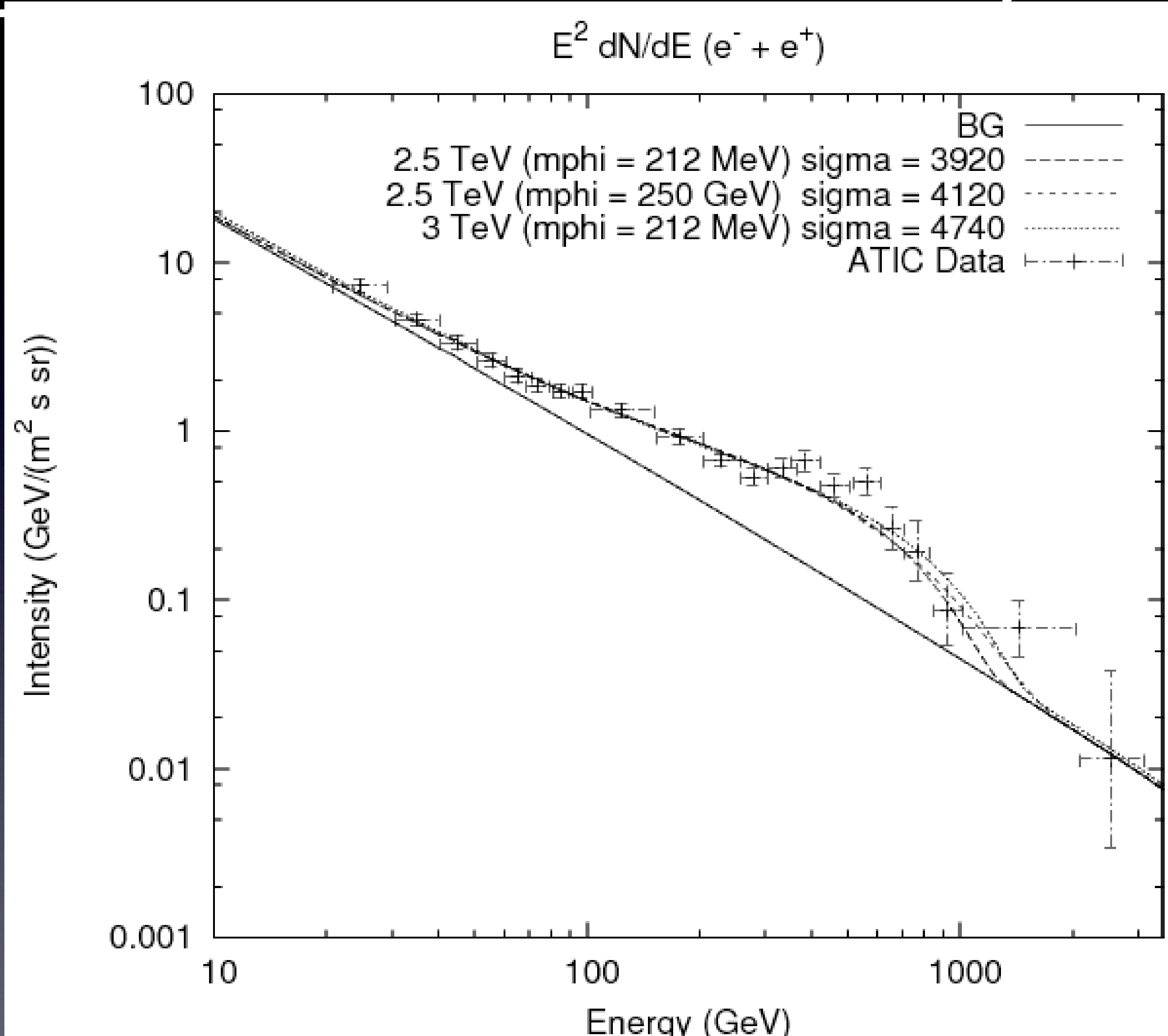
Background fitted to ATIC prelim. data
m_χ= 600 GeV, B.F. = 85
m_χ= 700 GeV, B.F. = 103
m_χ= 800 GeV, B.F. = 134
m_χ= 900 GeV, B.F. = 167
Preliminary Pamela Data 3
Preliminary PAMELA Results
m_χ: 600 to 900 GeV
Merritt (α = 0.17)
v_{Alfven} = 0 km/s
Positron Fraction
1
0.1
0.01
1
10
100
Energy (GeV)
Plot courtesy of Ilias Cholis

What about muons?

JPL



2.5 TeV Background
2.5 TeV (mphi = 212 MeV) sigma = 3280
2.5 TeV (mphi = 250 MeV) sigma = 3280
3.0 TeV Background
3.0 TeV (mphi = 212 MeV) sigma = 5210
Preliminary Pamela Data
Positron Fraction
1
0.1
0.01
1
10
100
1000
Energy (GeV)



E^2 dN/dE (e^- + e^+)
BG
2.5 TeV (mphi = 212 MeV) sigma = 3920
2.5 TeV (mphi = 250 GeV) sigma = 4120
3 TeV (mphi = 212 MeV) sigma = 4740
ATIC Data
Intensity (GeV/(m^2 s sr))
100
10
1
0.1
0.01
0.001
10
100
1000
Energy (GeV)

Toy model:

So an 800-900 GeV WIMP works well for both ATIC and PAMELA.

But the "Boost Factor" i.e. the cross section enhancement relative to the thermal relic $< \text{sigma } v>$ is ~ 150.

Should we be alarmed by this?

Two problems:

1. Such a large cross section cannot be obtained for "ordinary" annihilation channels straight to SM particles. < sigma v> must be at least as large at freeze-out and the WIMP density is too low.

2. Even if the cross section is 100 x higher than previously thought (by some mysterious mechanism), the π^0 gammas are too bright.

But...

1. The π^0 gamma problem is solved if the WIMP annihilates through some new light state, ϕ, that then goes to e^+e^- or $\mu^+ \mu^-$.

2. The existence of ϕ gives rise to an attractive interaction (via ϕ exchange) that enhances the cross section
--- *Sommerfeld enhancement.*

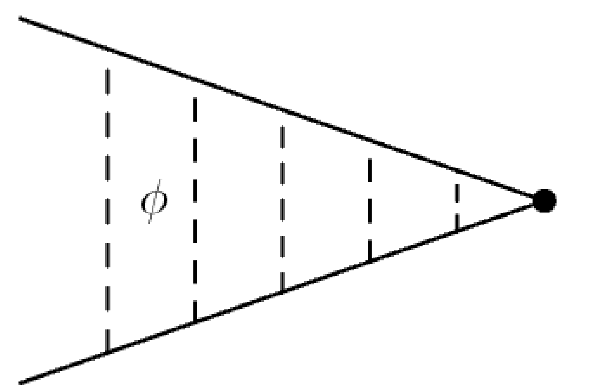
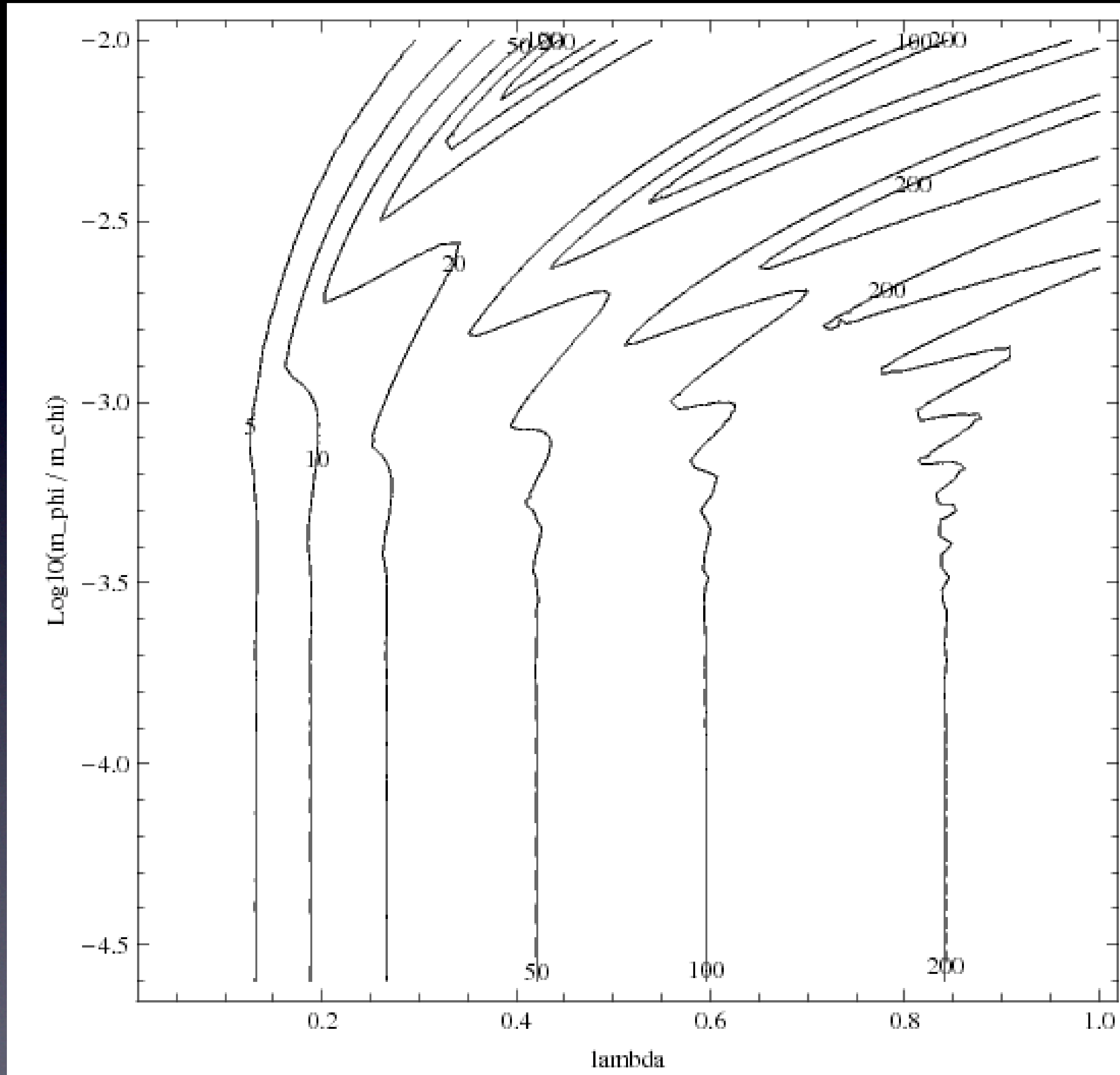


FIG. 1: Ladder diagram leading to Sommerfeld enhancement; the dot on the right represents all tree-level annihilation vertices.

How large is the Sommerfeld enhancement?

v_{rms}=150 km/s

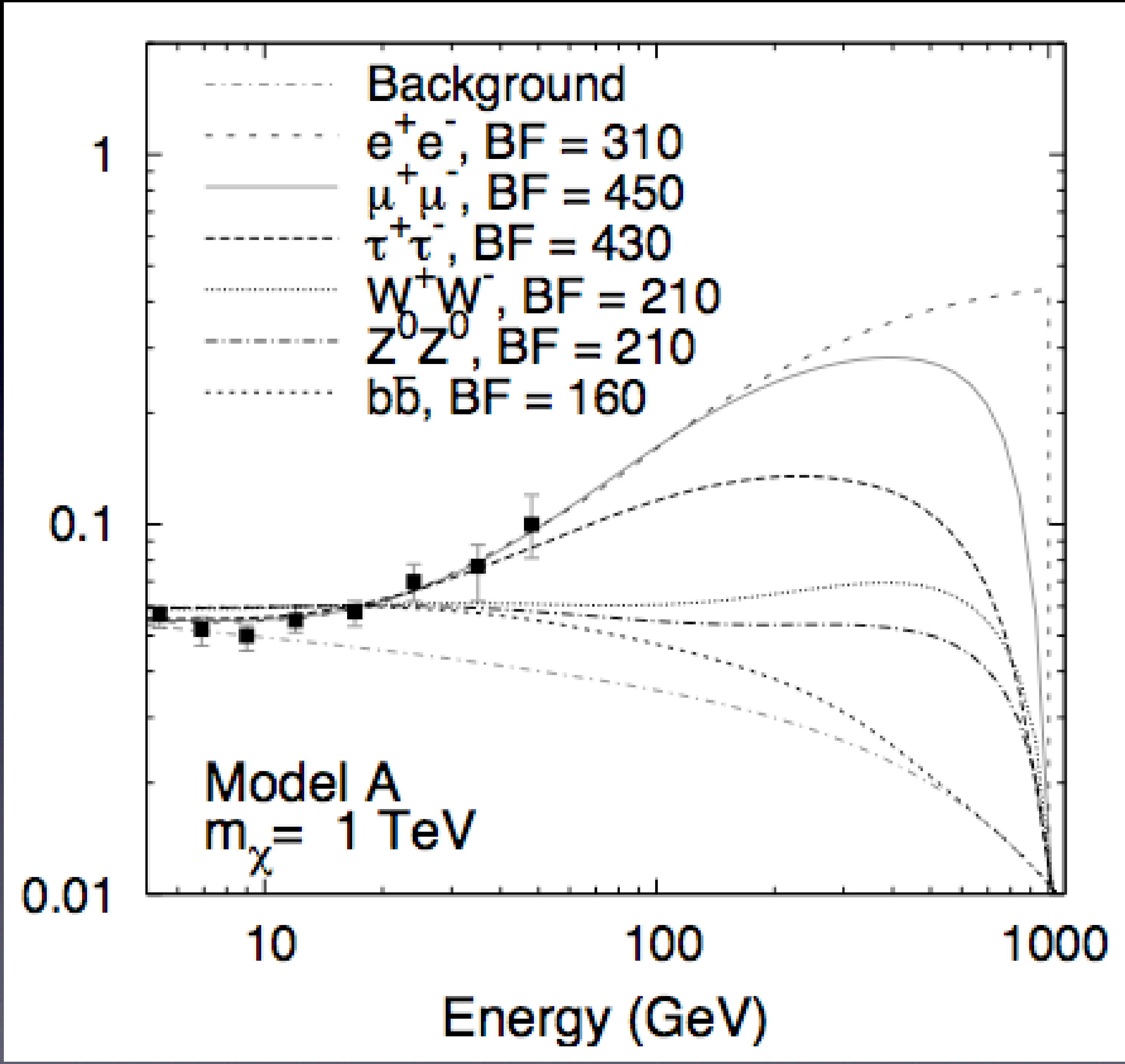

Log10(m_phi / m_chi)
lambda
−2.0
−2.5
−3.0
−3.5
−4.0
−4.5
0.2
0.4
0.6
0.8
1.0
5
10
20
50
100
200

Large Sommerfeld enhancement is possible.

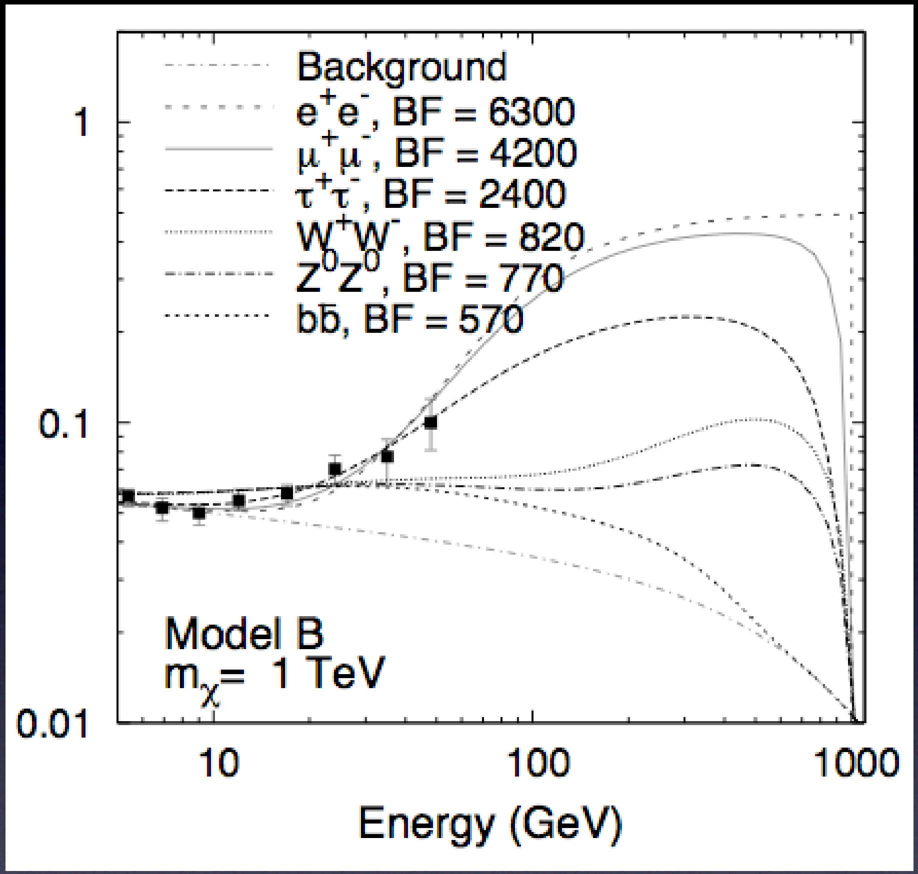
Also, subhalos become more important. The enhancement goes ~ $1/v$ so at low v (up to α/m_ϕ^2), so substructure contributes to annihilation more than we thought.

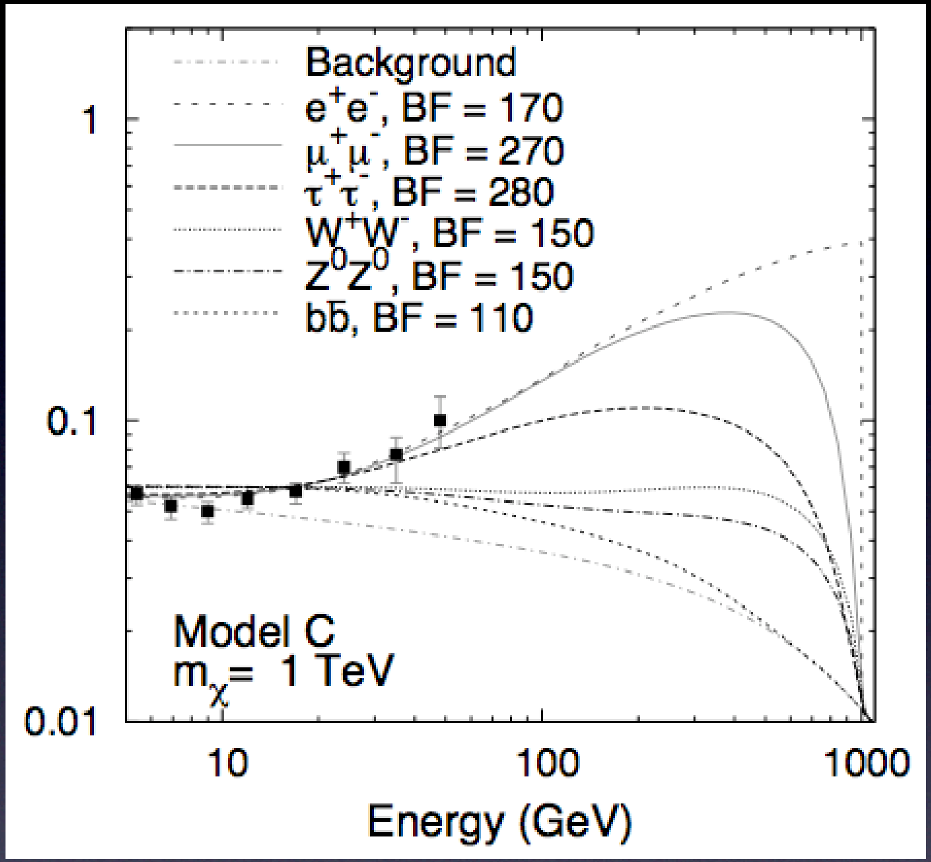
Are other annihilation channels possible?

JPL



Background
e+e-, BF = 310
μ+μ-, BF = 450
τ+τ-, BF = 430
W+W-, BF = 210
Z0Z0, BF = 210
bb̄, BF = 160
Model A
mχ= 1 TeV
1
0.1
0.01
10
100
1000
Energy (GeV)





(from Cholis et al. 0809.1683)

Just from PAMELA spectrum alone we see:
Decays to leptons OK; W, Z, b are bad.

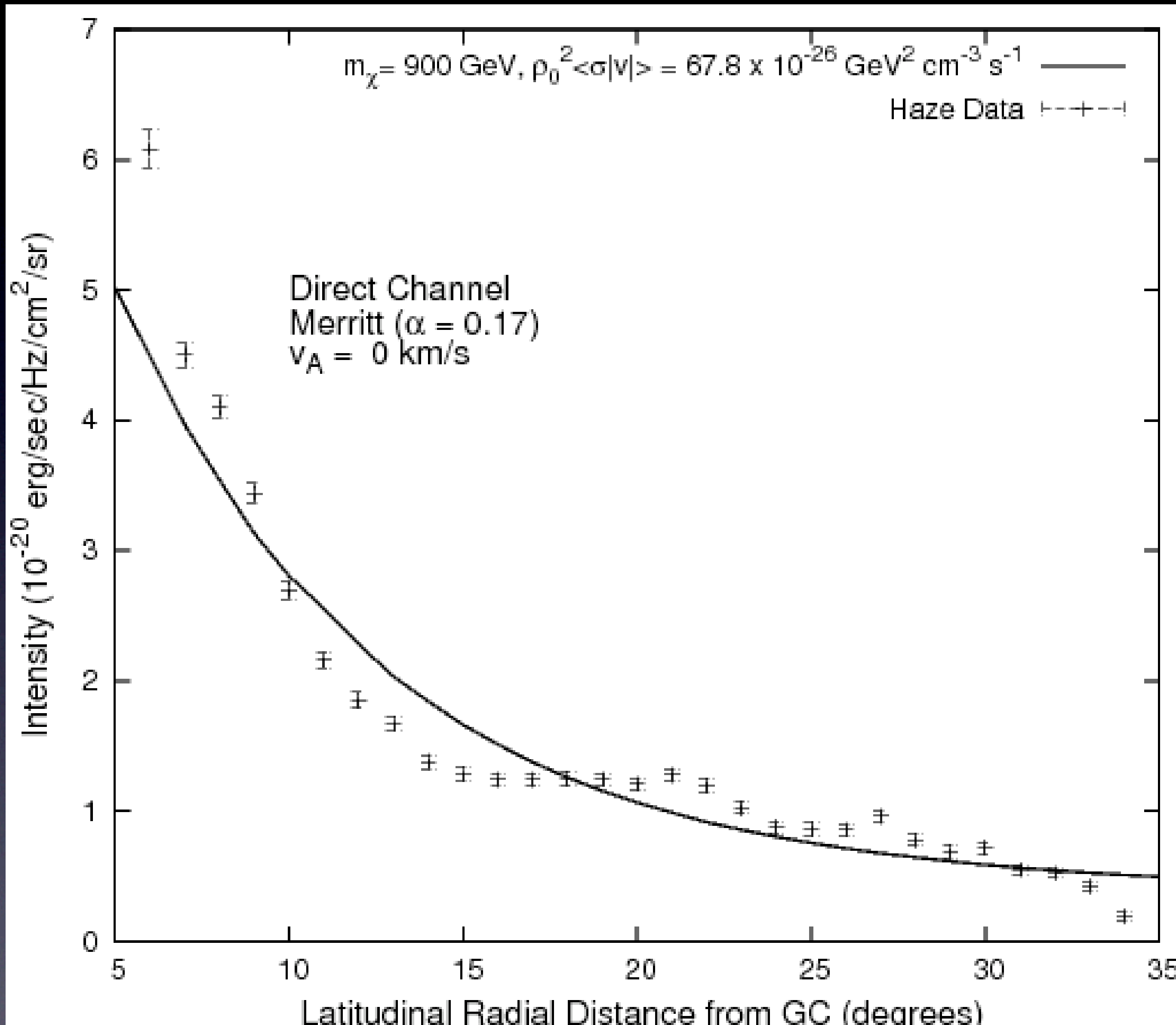
Large Sommerfeld enhancement is possible.

Also, subhalos become more important. The enhancement goes ~ 1/v so at low v (up to α/m_ϕ^2), so substructure contributes to annihilation more than we thought.

Conclusions so far: ATIC + PAMELA argue for a WIMP with mass ~ 800-900 GeV, which annihilates via a new light state, ϕ, with a cross section enhanced by its coupling to the ϕ.

Is the amplitude of the WMAP haze ok?

Yes.



m_χ= 900 GeV, $\rho_0^2\langle\sigma|v|\rangle$ = 67.8 x 10^{-26} GeV^2 cm^{-3} s^{-1}
Haze Data
Direct Channel
Merritt (α = 0.17)
v_A = 0 km/s
Intensity (10^{-20} erg/sec/Hz/cm^2/sr)
Latitudinal Radial Distance from GC (degrees)
0
1
2
3
4
5
6
7
5
10
15
20
25
30
35

So far, we have explained most of the excess electronic activity with one simple idea. Can we also explain INTEGRAL 511 keV line?

XDM - “eXciting dark matter”
(Finkbeiner & Weiner 2007)

Note: The mechanism I am about to present is an existence proof.

Other theories could exist which give a similar phenomenology.

The XDM Lagrangian includes:

- ϕ, a scalar which mediates the scattering
- χ ("ground" state) and χ* ("excited" state)
- λ-, the inelastic coupling,
- λ+, the elastic coupling, and
- αXDM, the mixing of the ϕ with the lightest Higgs.

$$\begin{aligned}\mathcal{L}_{XDM} &= \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \chi^\dagger\sigma_\mu\partial^\mu\chi + \chi_*^\dagger\sigma_\mu\partial^\mu\chi_* + \\ &+\frac{m_D}{2}\chi^2 - \frac{m_D}{2}\chi_*^2 - \lambda_+\phi\chi^2 - \lambda_+\phi\chi_*^2 - \\ &-\lambda_-\phi\chi\chi_* - V(\phi) + \alpha_{\mathrm{XDM}}\phi^2 hh^*.\end{aligned}$$

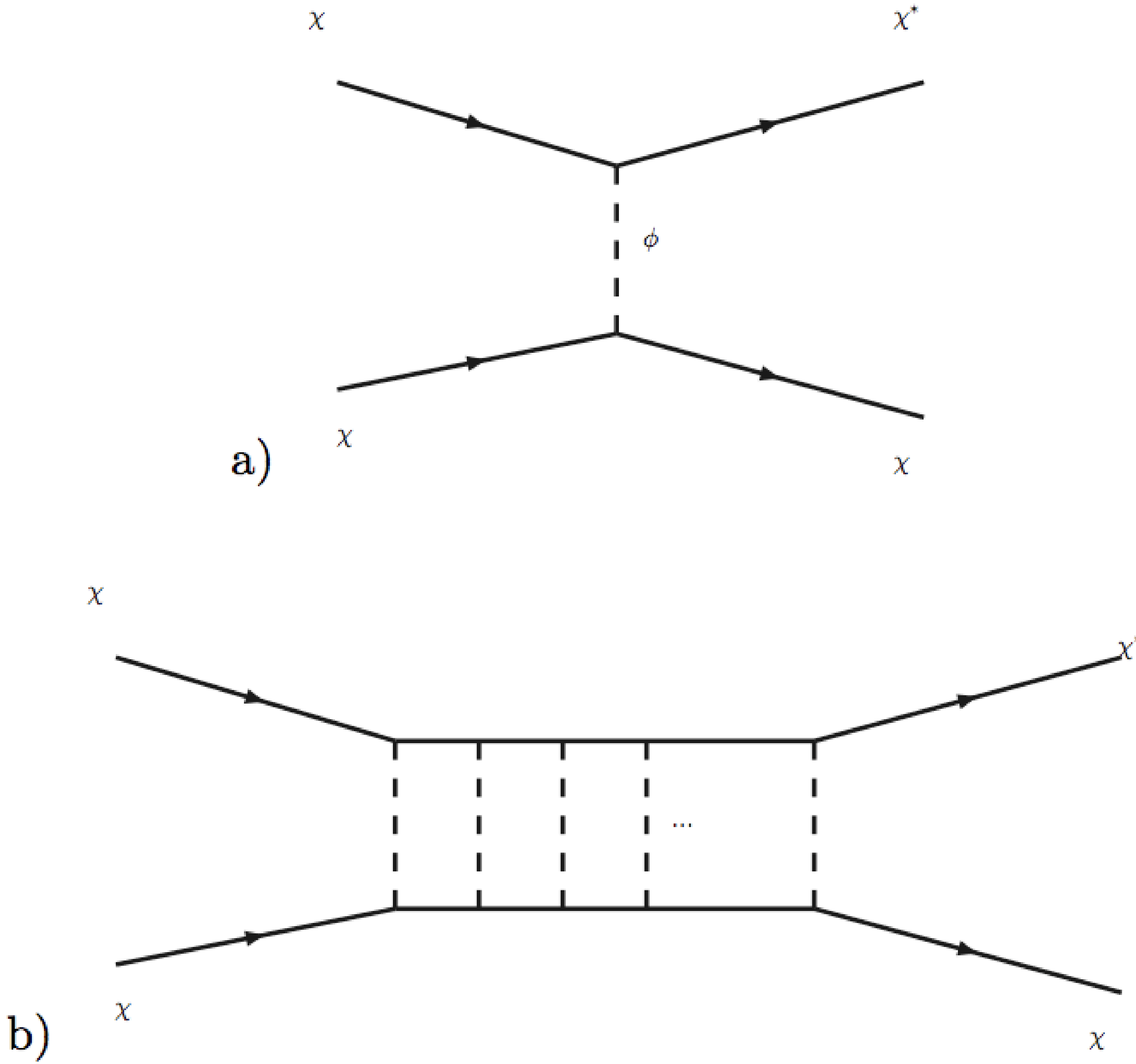


FIG. 4: Excitation diagrams for $\chi\chi \to \chi^{*}\chi$.

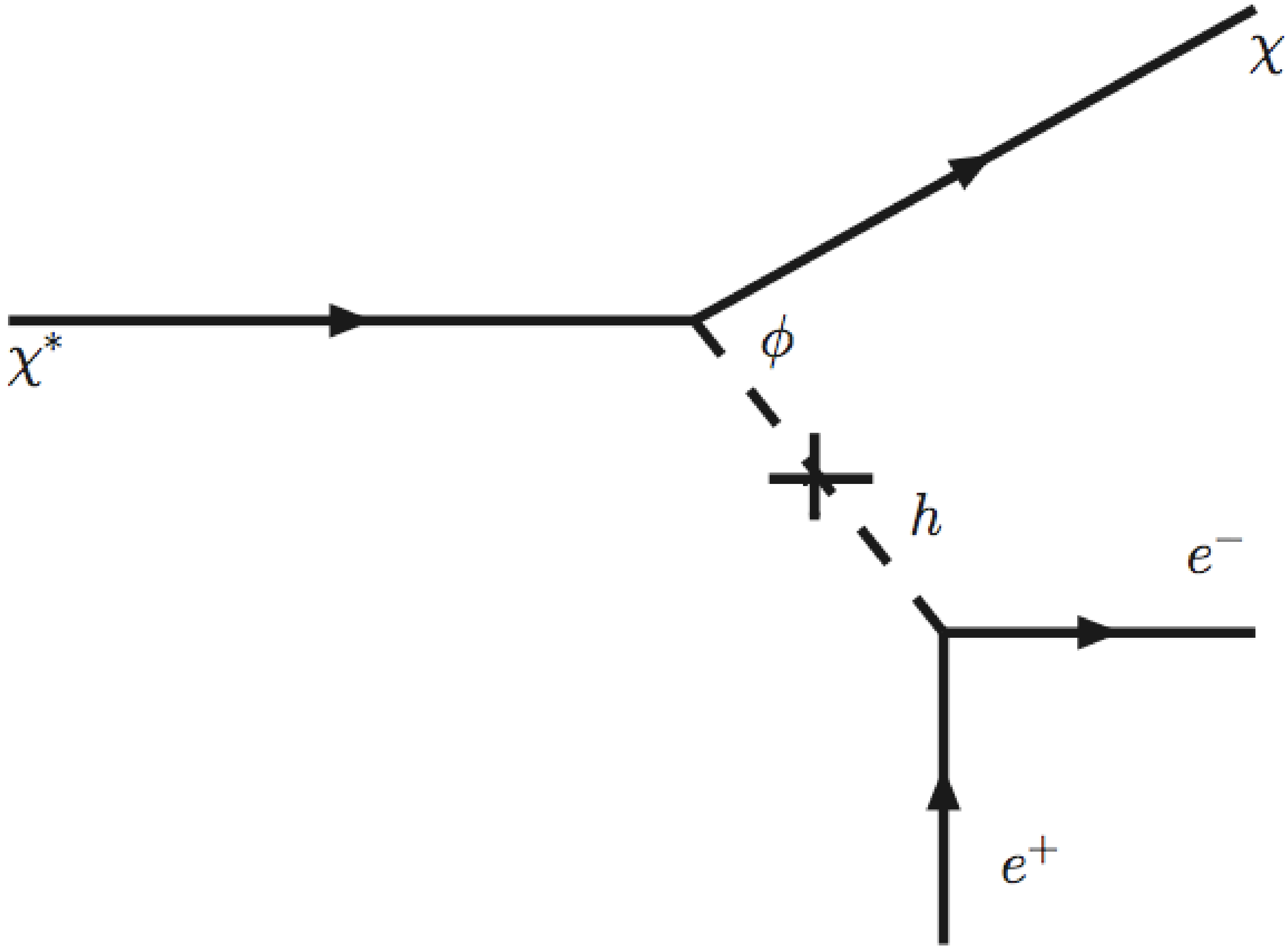


FIG. 5: Decay of the excited state into the ground state.

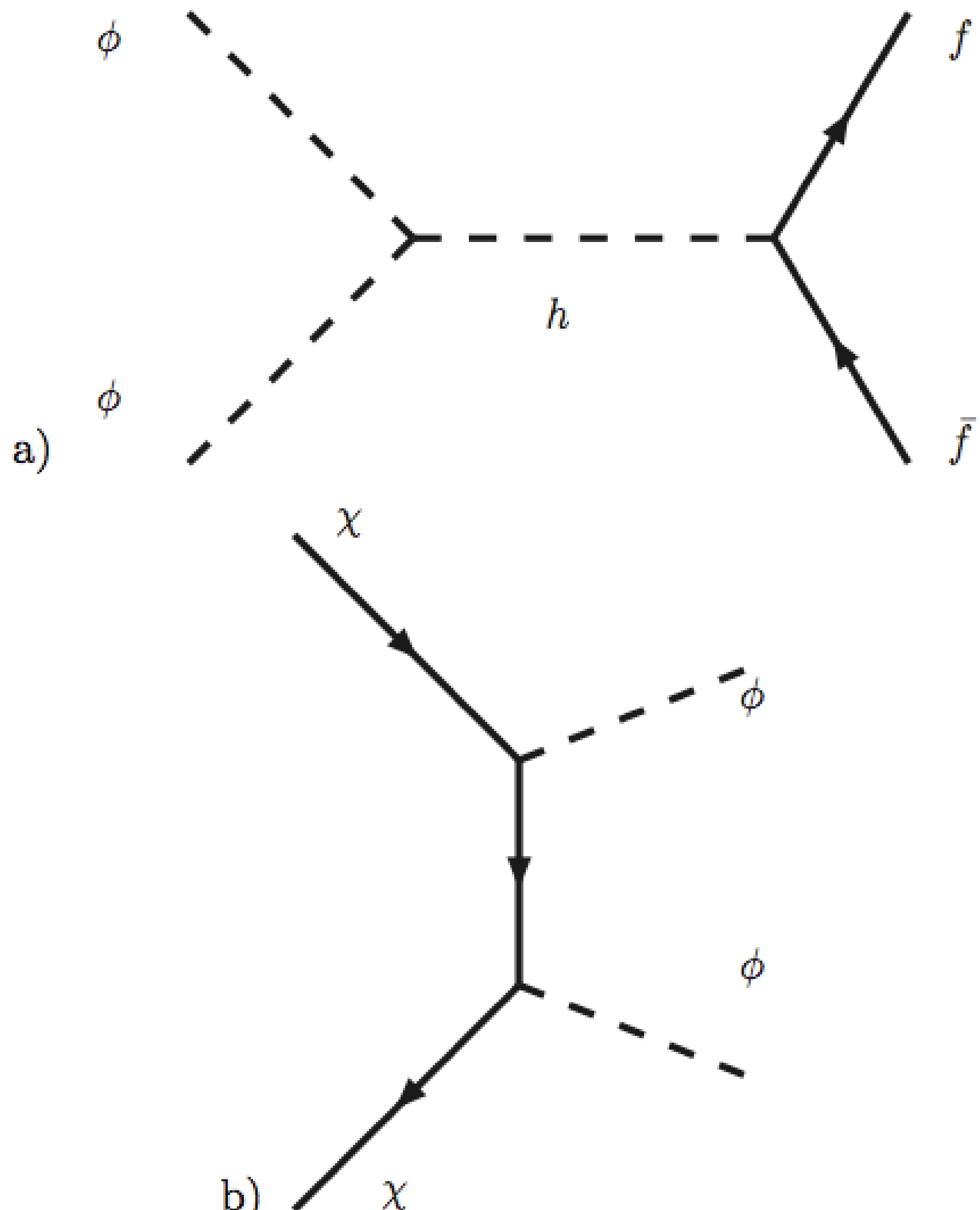


FIG. 6: Diagrams contributing to thermal equilibrium in the dark sector and between the dark sector and the visible sector.

Other details:

ϕ boson has mass of ~ 10-1000 MeV, correct cross-section for scattering (~ 10^{-26} cm^2)

BBN results are unchanged.

Interactions between χ, ϕ keep χ in thermal equilibrium until freeze-out; no change to thermal relic calculation (other than we have 2 species!)

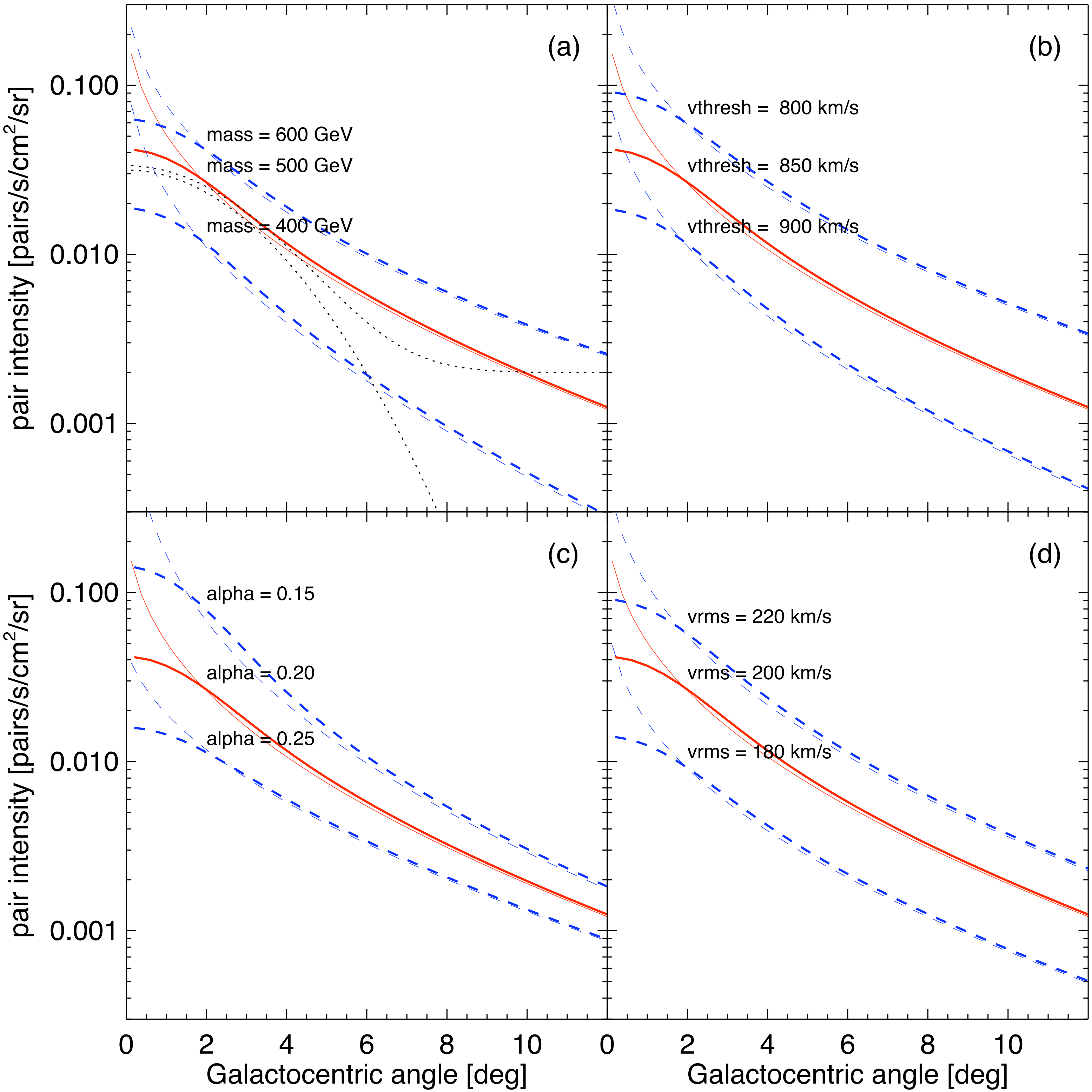
Weak-scale annihilation cross section gives correct density to be the DM (determined by gauge coupling)

Excitation arises from exchange of relatively light boson, so naturally has larger cross section than annihilation
(which is suppressed by the large WIMP mass)

$\sigma_{\mathrm{ann}} / \sigma_{\mathrm{scatter}} \sim 10^{-5}$
$\delta / M \sim 10^{-5}$

This feature is essential if XDM is to explain both the haze and the 511 keV line.

So, how does the model compare to INTEGRAL?



(a)
mass = 600 GeV
mass = 500 GeV
mass = 400 GeV
(b)
vthresh = 800 km/s
vthresh = 850 km/s
vthresh = 900 km/s
(c)
alpha = 0.15
alpha = 0.20
alpha = 0.25
(d)
vrms = 220 km/s
vrms = 200 km/s
vrms = 180 km/s
pair intensity [pairs/s/cm²/sr]
0.100
0.010
0.001
0
2
4
6
8
10
Galactocentric angle [deg]

Why is there only ~ one parameter to tune?

The mass of the ϕ along with some other (not fine-tuned!) couplings determines both the scattering cross section AND the χ mass splitting.

This is a very appealing feature of the model.

We use a fairly large coupling constant (0.18) which requires resumming the ladder diagrams, but gives a nice cross section without violating the unitarity bound.

Simplest model:

~NFW DM density profile in Milky Way
100 GeV particle mass
Annihilation through several SM channels
$\langle\sigma v\rangle = 2 \times 10^{-26}$ cm^3/s (thermal relic Xsec)
10 microGauss field
This extremely simple model gives roughly the right power, spectrum, and spatial distribution.

Solve the diffusion energy-loss equation in spherical coordinates:

$$\frac{d}{dt}n(E,\mathbf{x}) = \nabla \cdot (K(E,\mathbf{x})\nabla n) + \frac{\partial}{\partial E}\left[b(E,\mathbf{x})n\right] + Q(E,\mathbf{x})$$

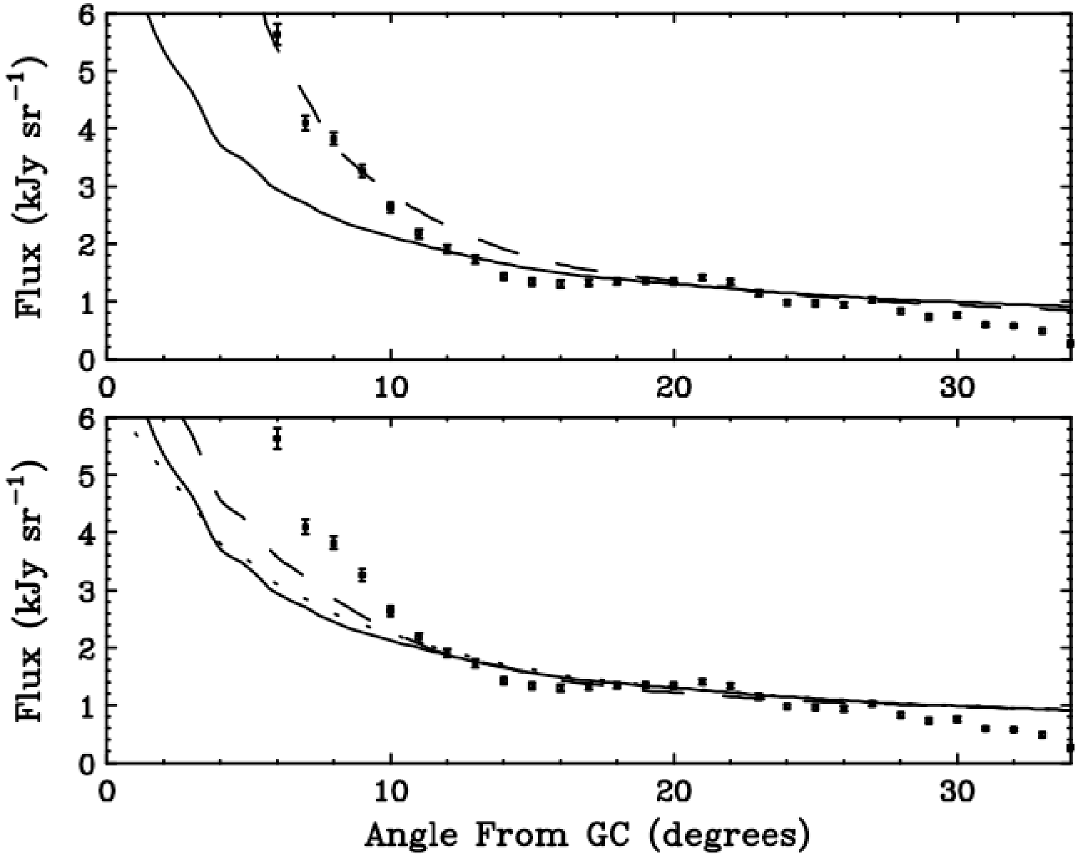
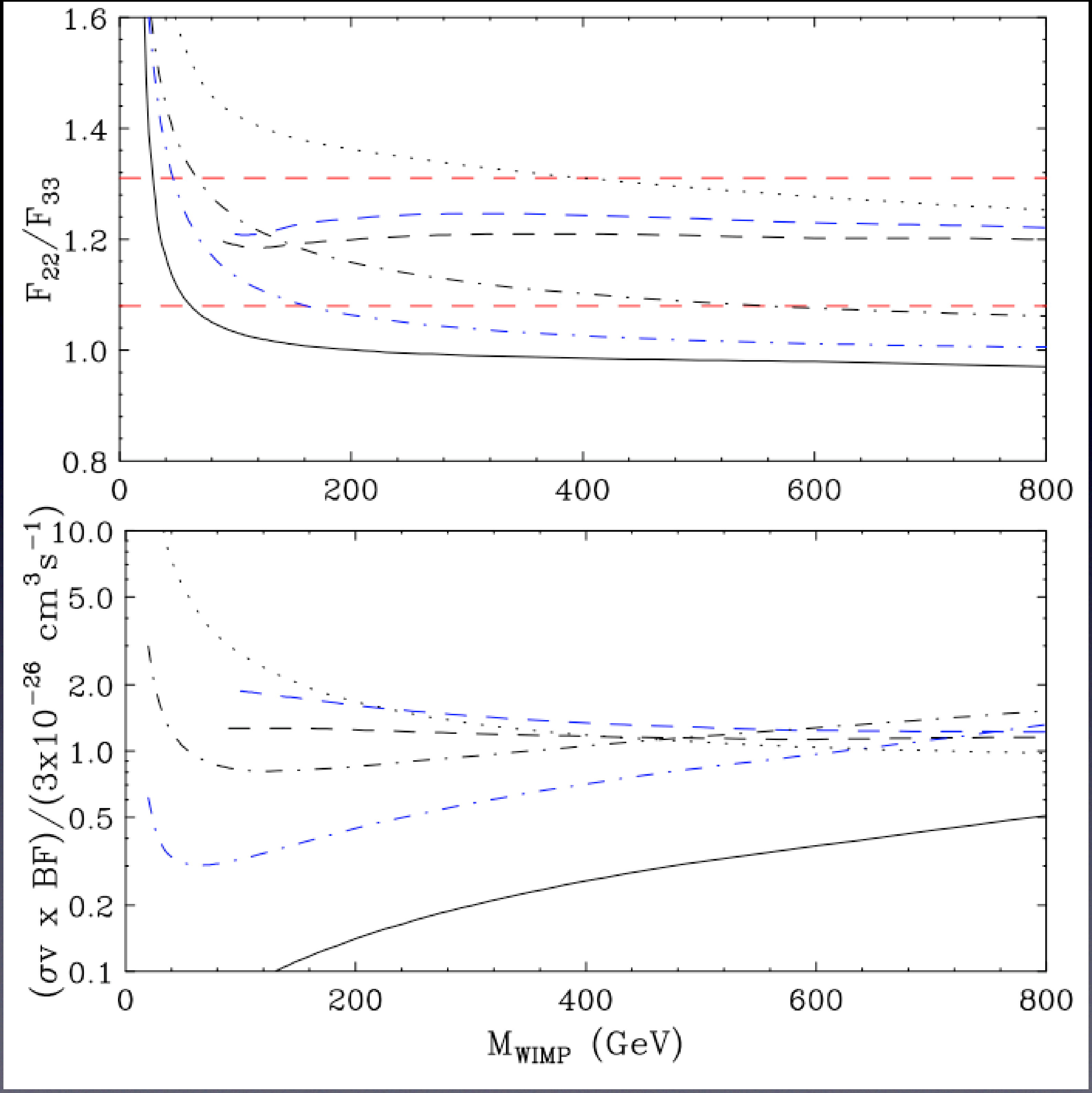


FIG. 2: The specific intensity of microwave emission in the 22 GHz WMAP channel as a function of the angle from the Galactic Center, compared to the synchotron emission from the annihilation products of a 100 GeV WIMP annihilating to e^+e^-. In the upper frame, our default diffusion parameters have been used. The solid line denotes the choice of an NFW halo profile, while the dashed line is the result from a profile with a somewhat steeper inner slope, with $\rho(r) \propto r^{-1.2}$. In the lower frame, we have used an NFW profile with our default propagation parameters (solid), and with a smaller diffusion zone with $L = 2$ kpc (dashes), and a longer energy loss time of $\tau(1\,\mathrm{GeV}) = 4 \times 10^{15}$ s (dotted).

Hooper, Finkbeiner, & Dobler (2007) arXiv:0705.365



1.6
1.4
1.2
1.0
0.8
F_{22}/F_{33}
0
200
400
600
800
10.0
5.0
2.0
1.0
0.5
0.2
0.1
$(\sigma v \times BF)/(3\times10^{-26}\ cm^3s^{-1})$
0
200
400
600
800
M_{WIMP} (GeV)

Bottom line:

If DM is a WIMP, and
If the WIMP is a thermal relic, and
If s-wave annihilation is not too subdominant, then

the WIMP should produce a synchrotron signal with the amplitude, shape, and spectrum of the WMAP haze.

If true, this is the most important discovery of WMAP.

Conclusions (from WMAP):

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WMAP data are consistent with the Draine & Lazarian (1998) spinning dust model, and inconsistent with the null hypothesis of no spinning dust.

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WMAP data are consistent with the Draine & Lazarian (1998) spinning dust model, and inconsistent with the null hypothesis of no spinning dust.

Even including spinning dust in the fit, there is still too much emission in the center (the haze) and its origin involves either exotic astrophysics or new physics.

Future work (with *Planck*)

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* Refine measurement of the haze spectrum.

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* Refine measurement of the haze spectrum.
  Better CMB map -> less CMB cross-correlation

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* 2 FDS 99 components: are they real? Polarization

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  signature? Correlation with extinction anomalies
  (from SDSS / PS-1) ?

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* Refine measurement of the haze spectrum.
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* Akari dust map: better resolution, better T_dust,

Future work (with *Planck*)

* Refine measurement of the haze spectrum.
  Better CMB map -> less CMB cross-correlation
  bias -> better haze measurement

* 2 FDS 99 components: are they real? Polarization signature? Correlation with extinction anomalies (from SDSS / PS-1) ?

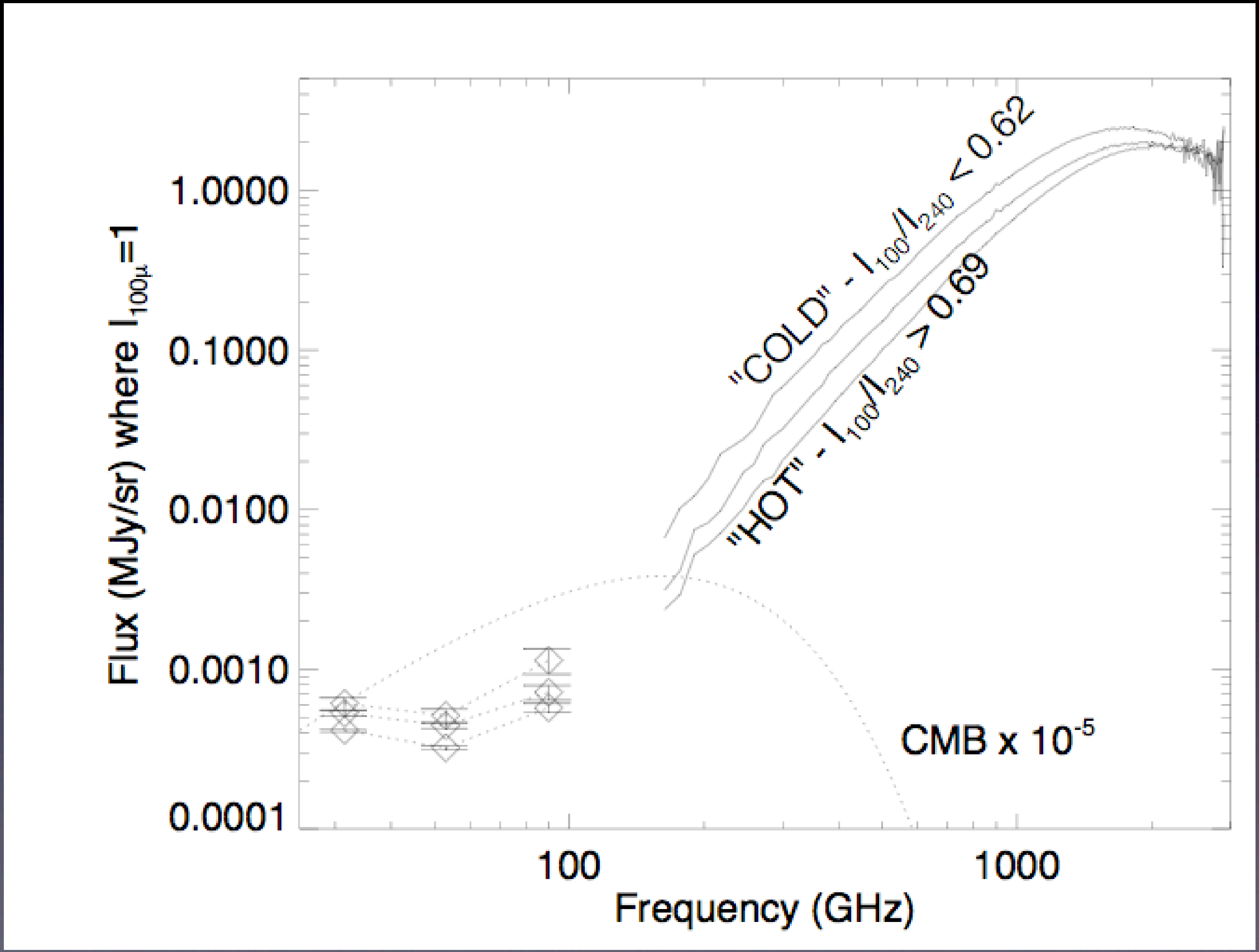
* Akari dust map: better resolution, better T_dust, better point source subtraction. -> better dust

Future work (with *Planck*)

* Refine measurement of the haze spectrum.
  Better CMB map -> less CMB cross-correlation bias -> better haze measurement

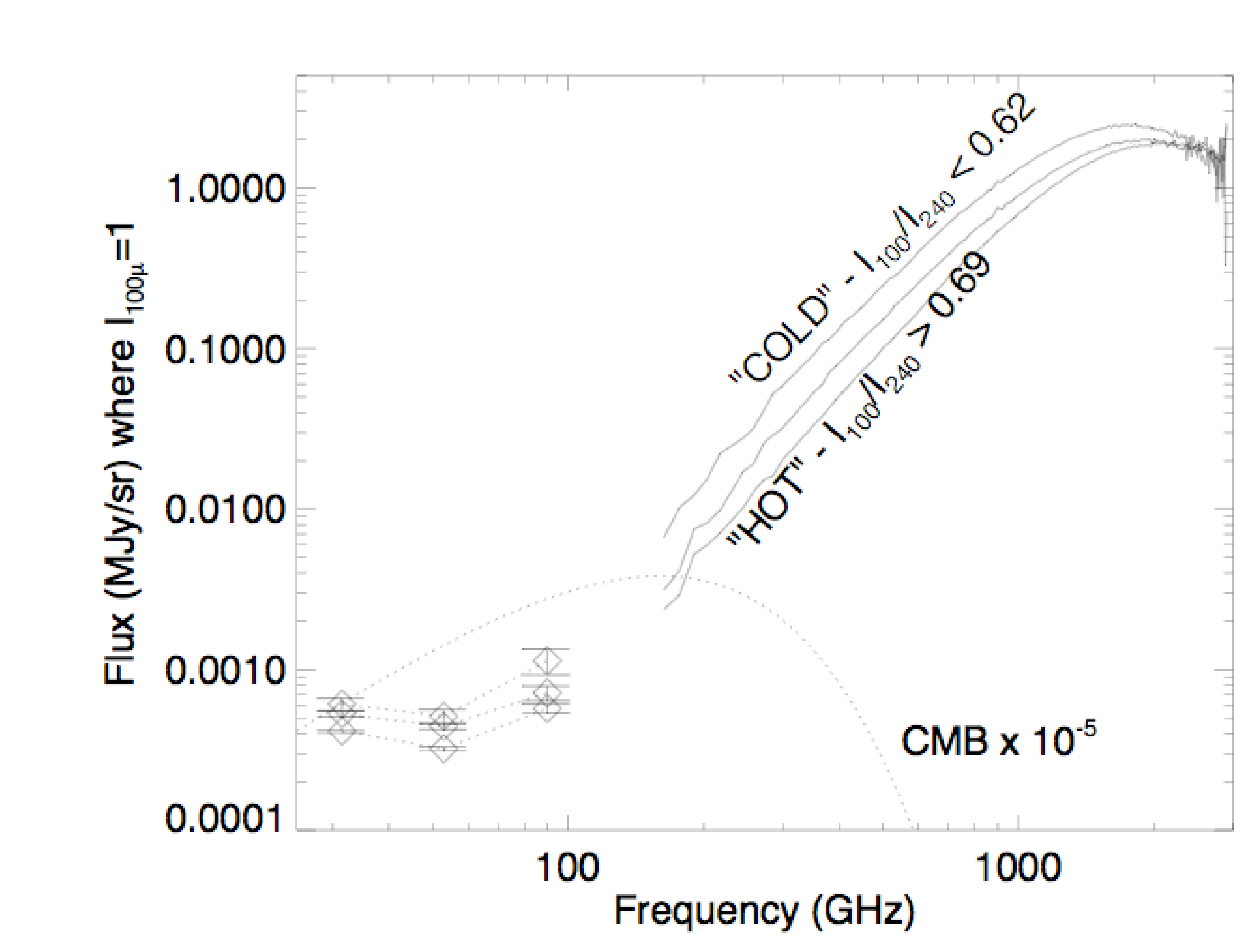
* 2 FDS 99 components: are they real? Polarization signature? Correlation with extinction anomalies (from SDSS / PS-1) ?

* Akari dust map: better resolution, better T_dust, better point source subtraction. -> better dust template for *Planck*.

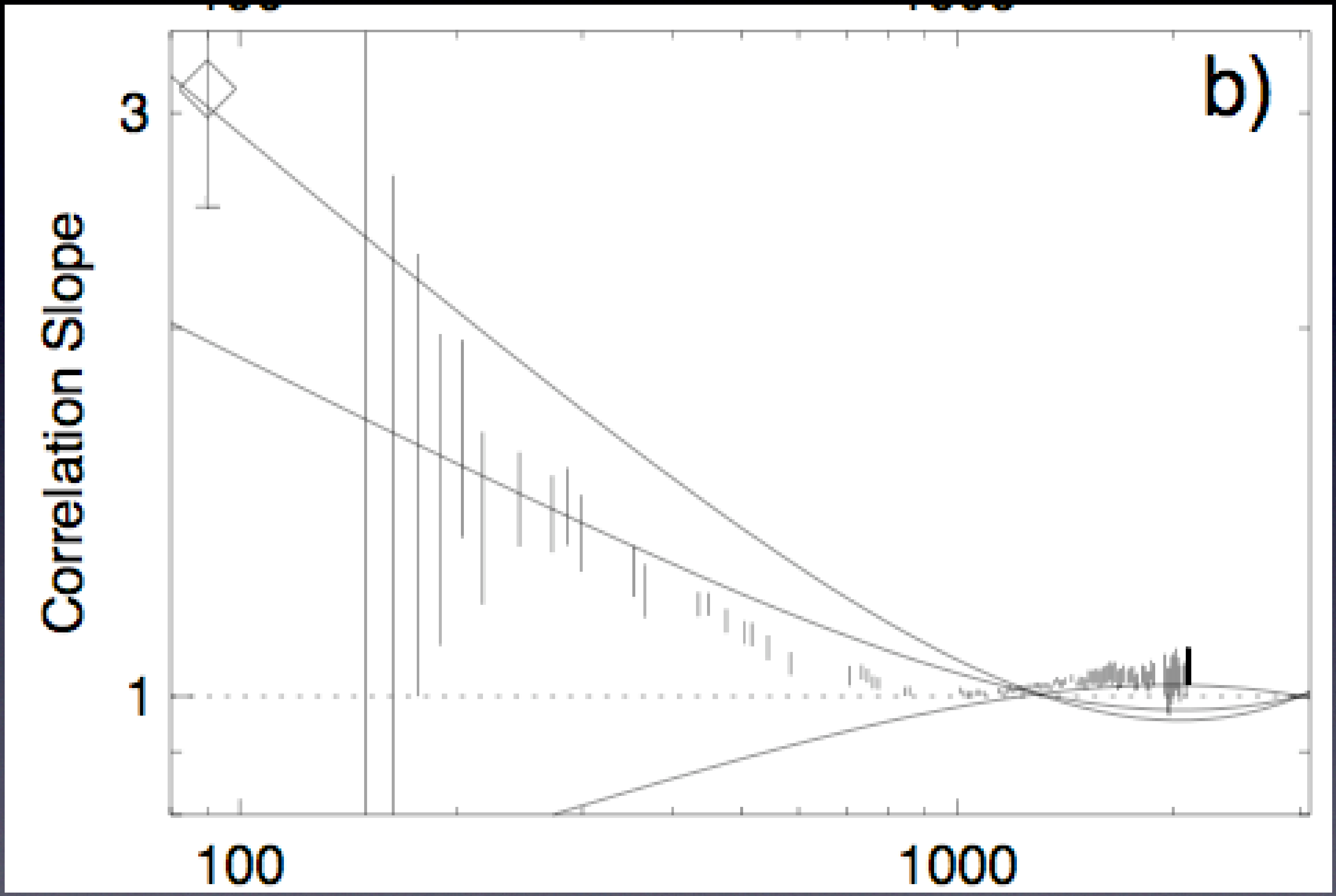


Flux (MJy/sr) where $I_{100\mu}=1$
1.0000
0.1000
0.0100
0.0010
0.0001
100
1000
Frequency (GHz)
"COLD" - $I_{100}/I_{240} < 0.62$
"HOT" - $I_{100}/I_{240} > 0.69$
CMB x 10^{-5}

FDS99:

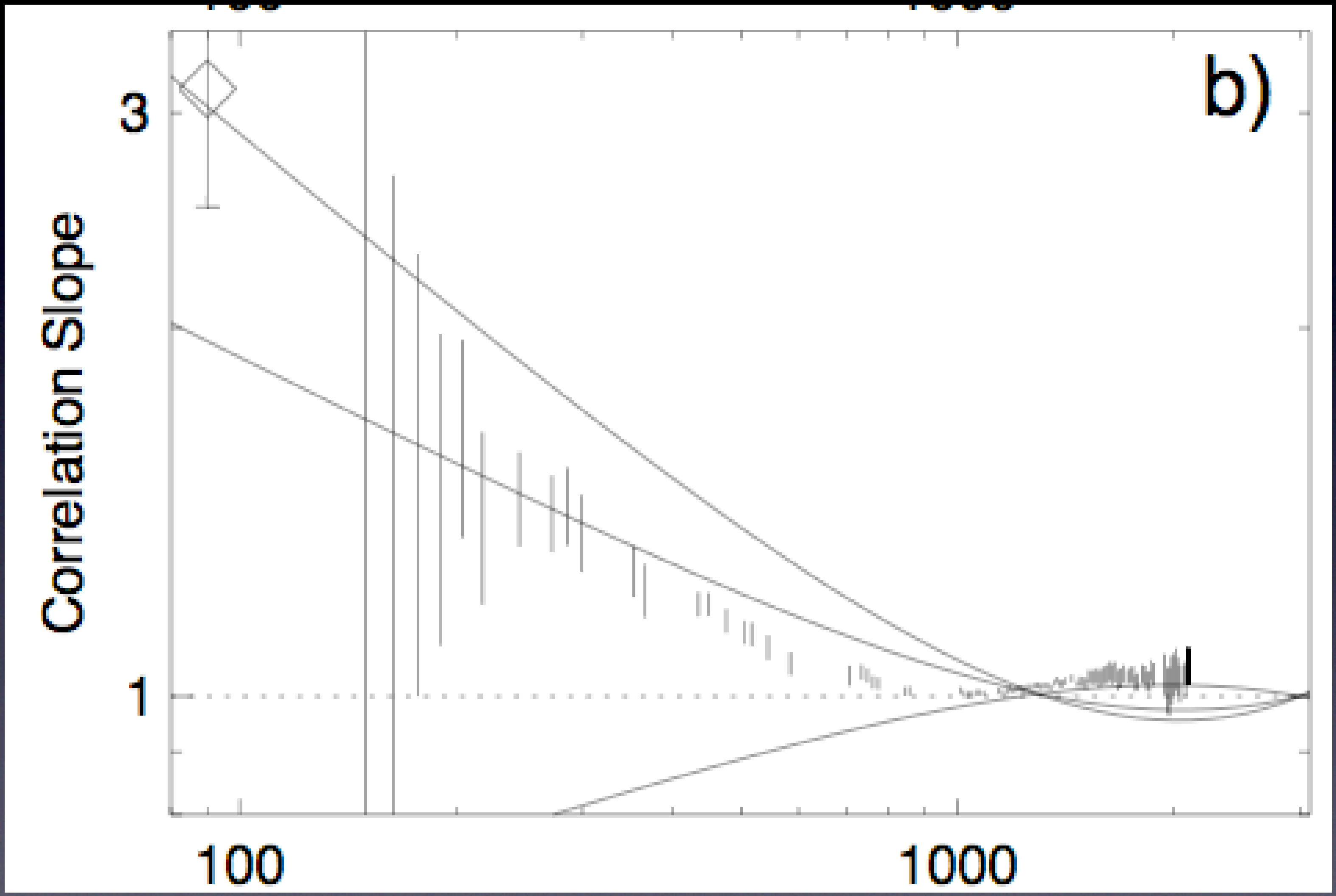


1.0000
0.1000
0.0100
0.0010
0.0001
Flux (MJy/sr) where $I_{100\mu}$=1
"COLD" - I_{100}/I_{240} < 0.62
"HOT" - I_{100}/I_{240} > 0.69
CMB x 10^{-5}
100
1000
Frequency (GHz)



b)
Correlation Slope
3
1
100
1000

FDS99: one-component models (1.5, 1.7, 2.0, 2.2)



FDS99: simple idea

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No one power-law component fits the FIRAS

FDS99: simple idea

No one power-law component fits the FIRAS data.

FDS99: simple idea

No one power-law component fits the FIRAS data.

Try two components with different power laws,

FDS99: simple idea

No one power-law component fits the FIRAS data.

Try two components with different power laws, different optical / microwave opacity ratios.

FDS99: simple idea

No one power-law component fits the FIRAS data.

Try two components with different power laws, different optical / microwave opacity ratios.

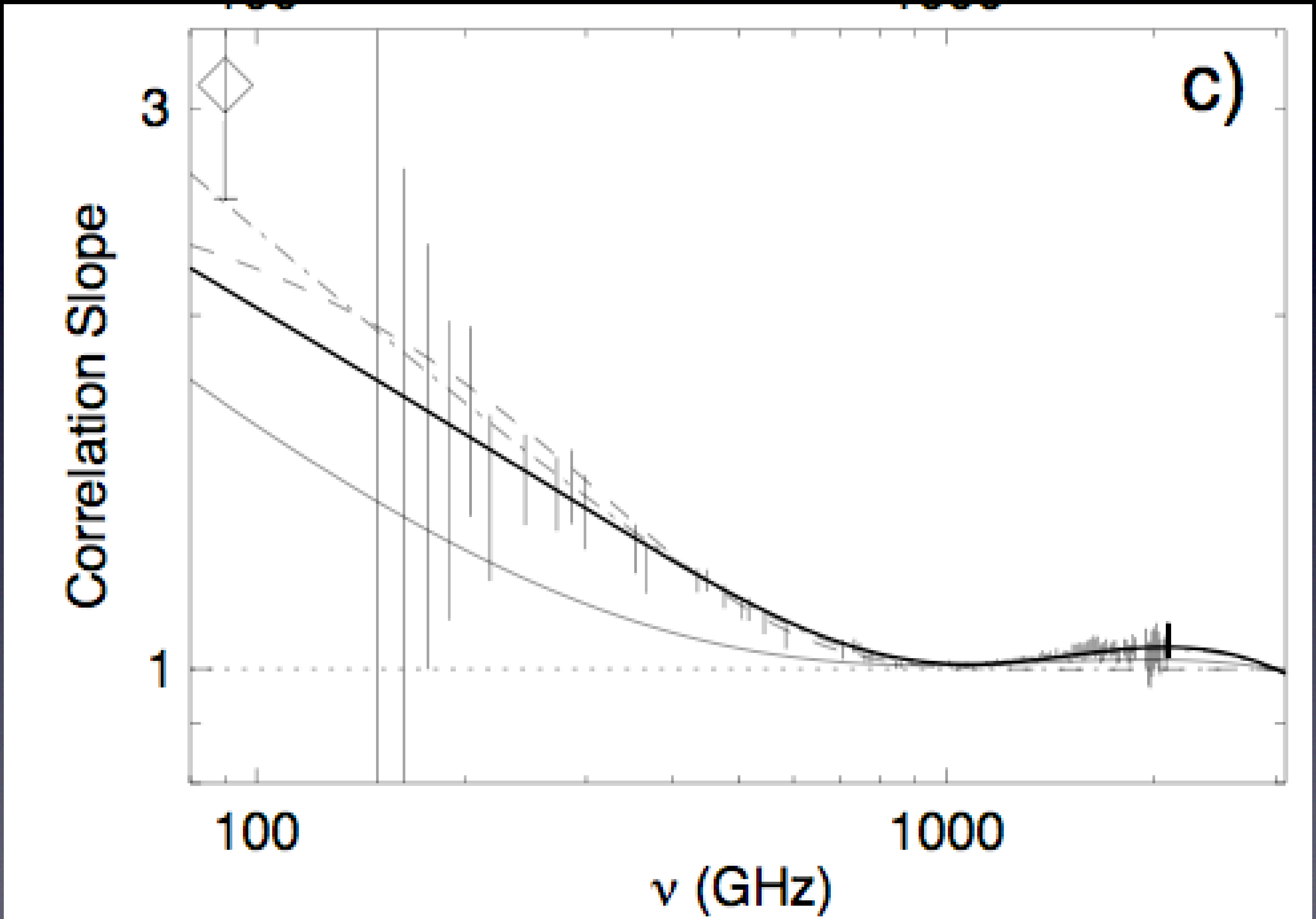
Fit 4 parameters over the full sky (*not* per pixel)

FDS99: simple idea

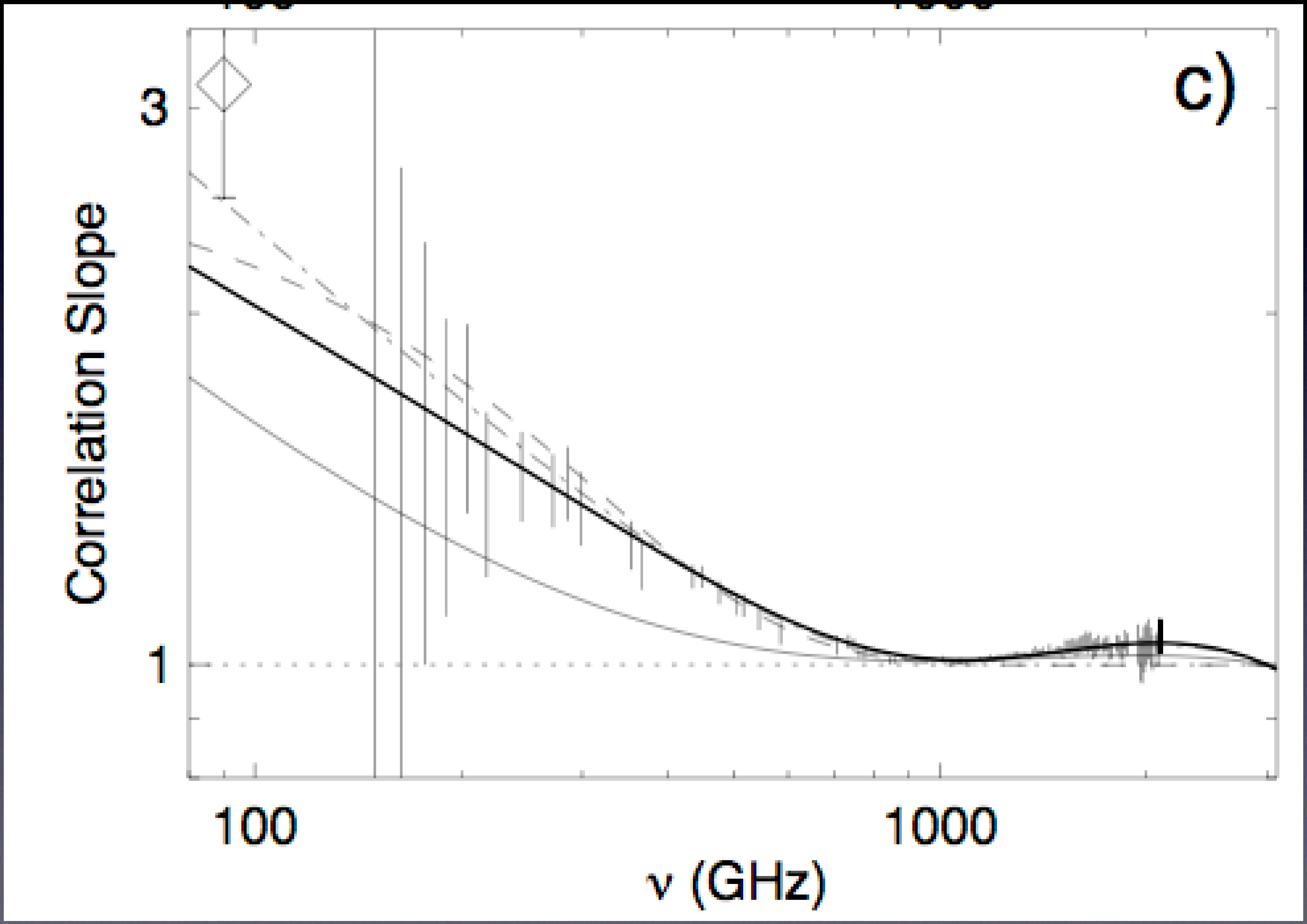
No one power-law component fits the FIRAS data.

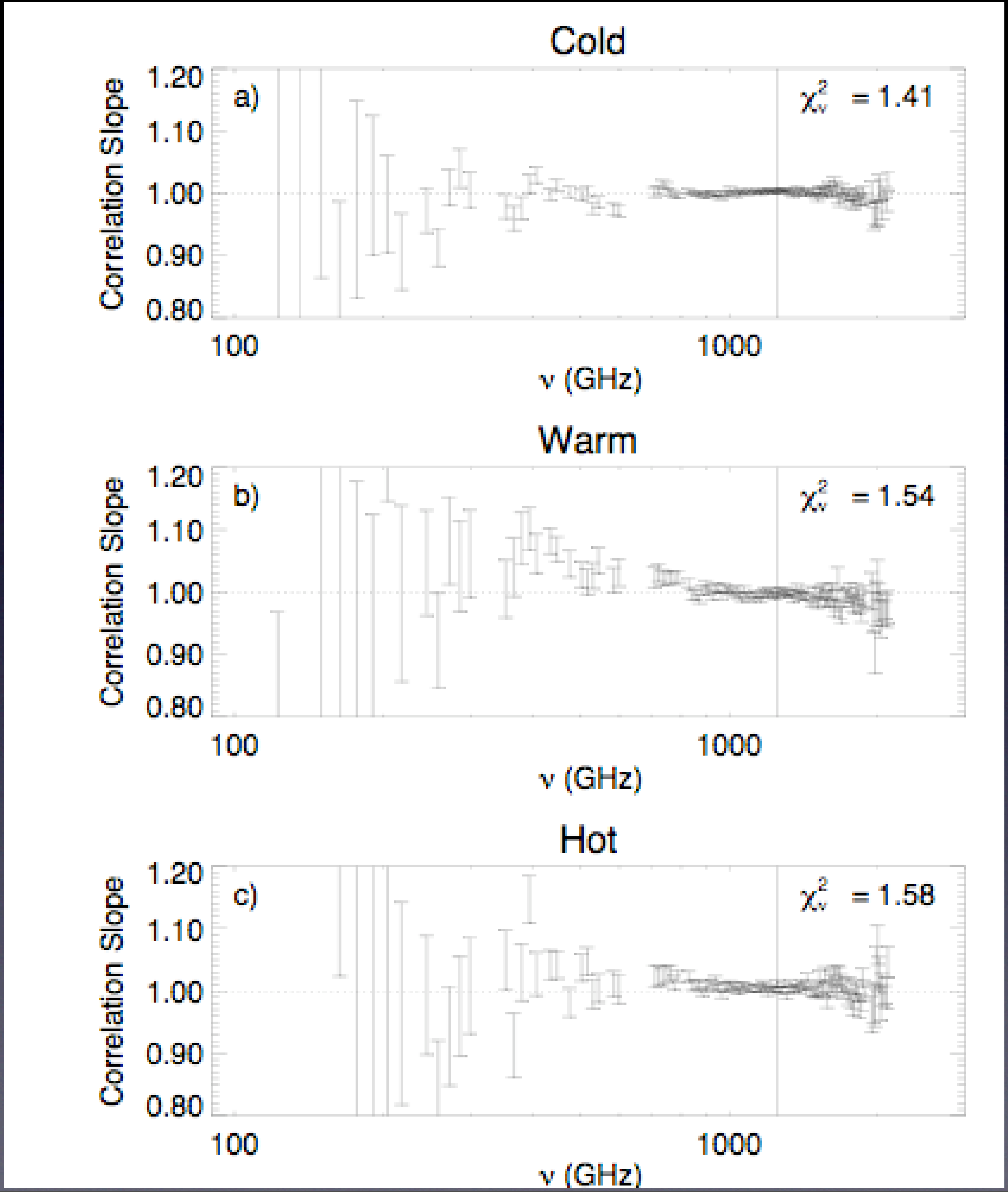
Try two components with different power laws, different optical / microwave opacity ratios.

Fit 4 parameters over the full sky (*not* per pixel) for dramatic reduction in chi-squared.

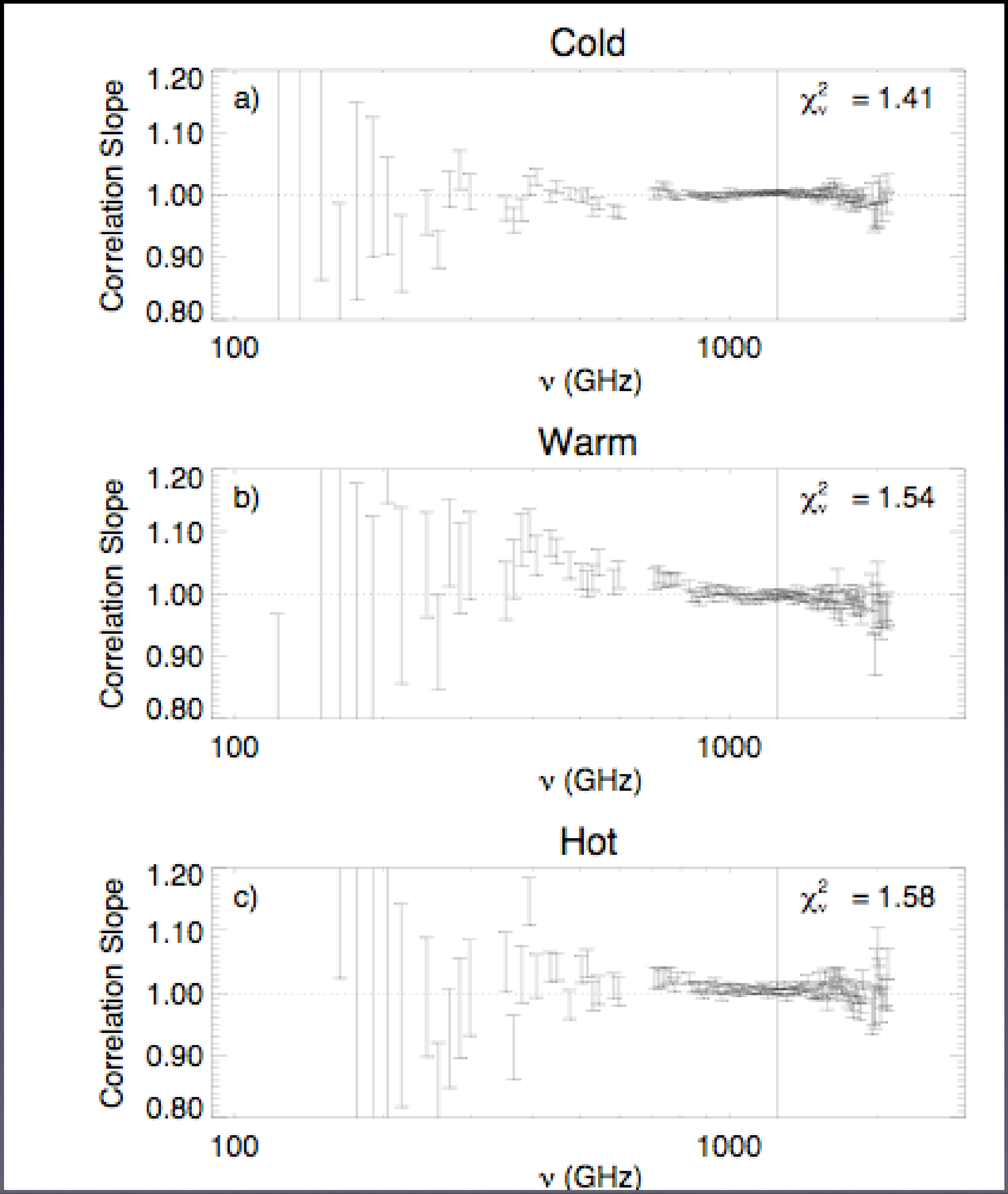

c)
Correlation Slope
3
1
100
1000
ν (GHz)

FDS99: two-component models




Cold
a)
χ^2_ν = 1.41
Correlation Slope
1.20
1.10
1.00
0.90
0.80
100
1000
ν (GHz)
Warm
b)
χ^2_ν = 1.54
Correlation Slope
1.20
1.10
1.00
0.90
0.80
100
1000
ν (GHz)
Hot
c)
χ^2_ν = 1.58
Correlation Slope
1.20
1.10
1.00
0.90
0.80
100
1000
ν (GHz)

FDS99:



Cold
a)
χ^2_ν = 1.41
Correlation Slope
1.20
1.10
1.00
0.90
0.80
100
1000
ν (GHz)
Warm
b)
χ^2_ν = 1.54
Correlation Slope
1.20
1.10
1.00
0.90
0.80
100
1000
ν (GHz)
Hot
c)
χ^2_ν = 1.58
Correlation Slope
1.20
1.10
1.00
0.90
0.80
100
1000
ν (GHz)

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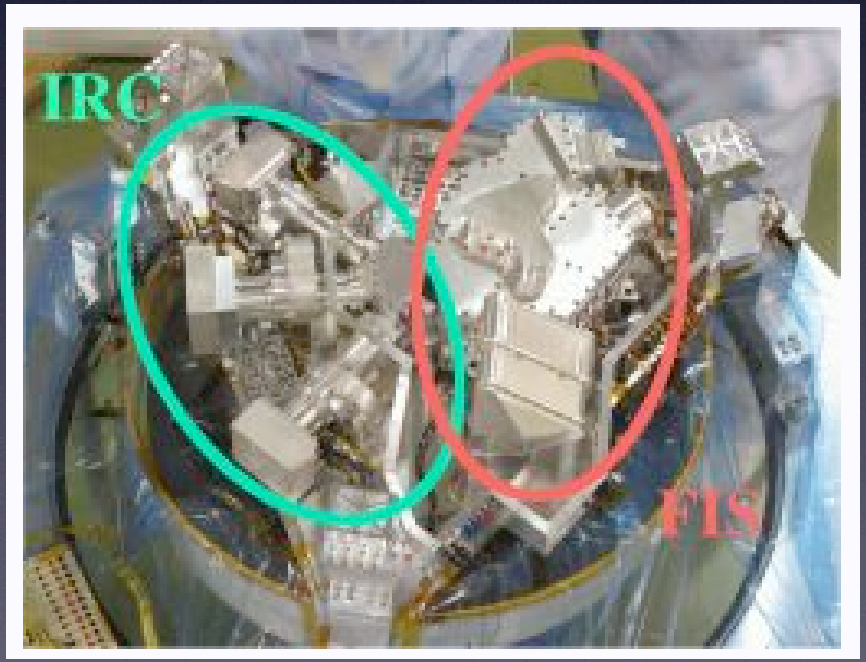
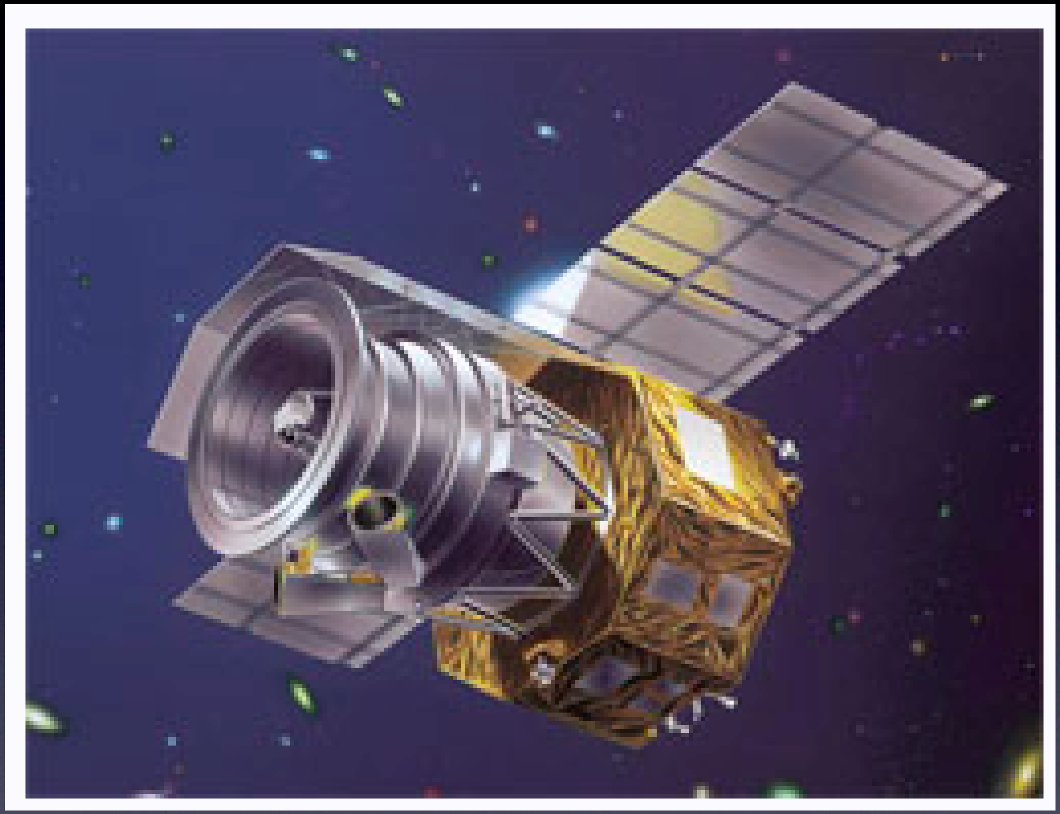
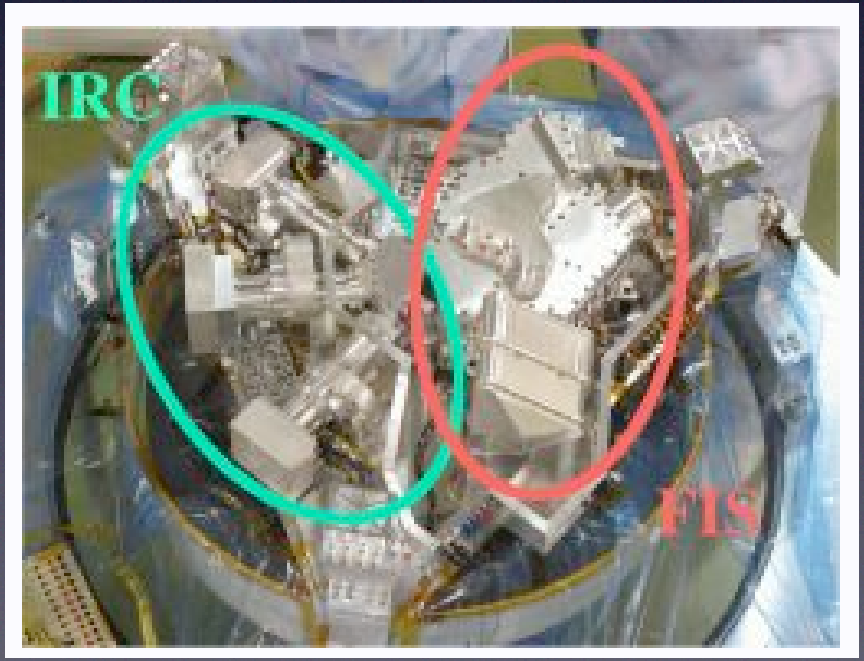
This is a good description of the data, but does it correspond to reality? i.e. does emission from two components actually dominate?



IRC
FIS

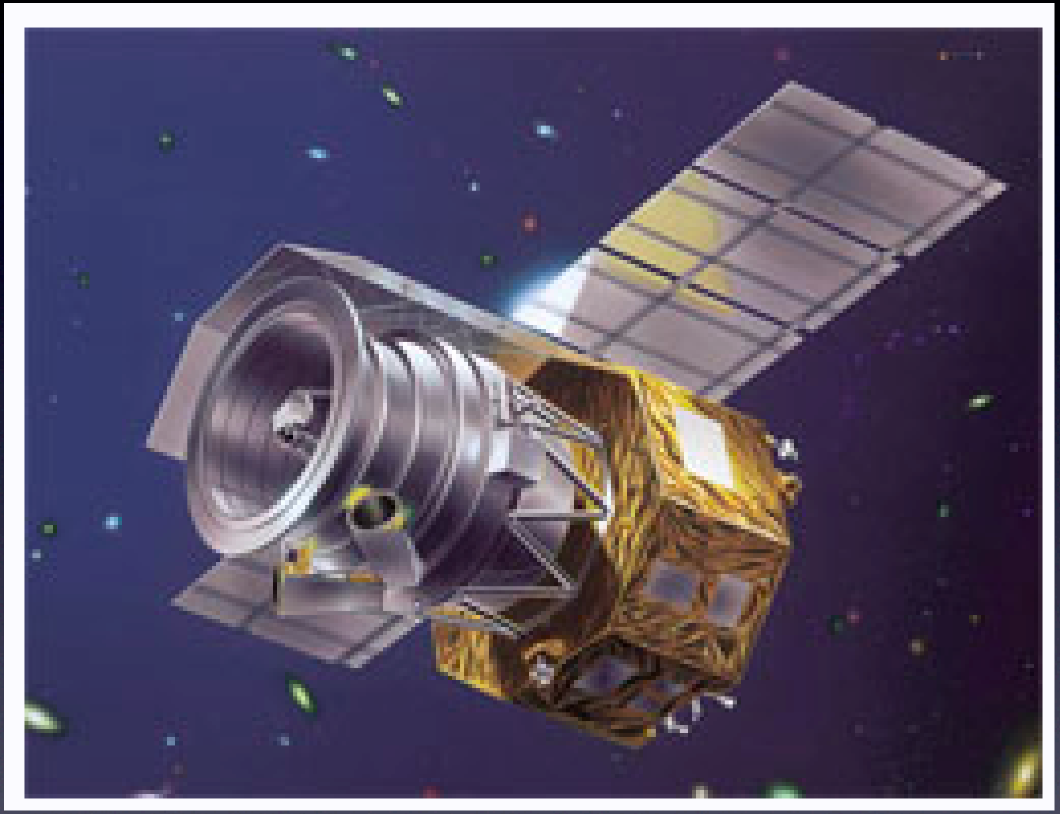
Last topic:

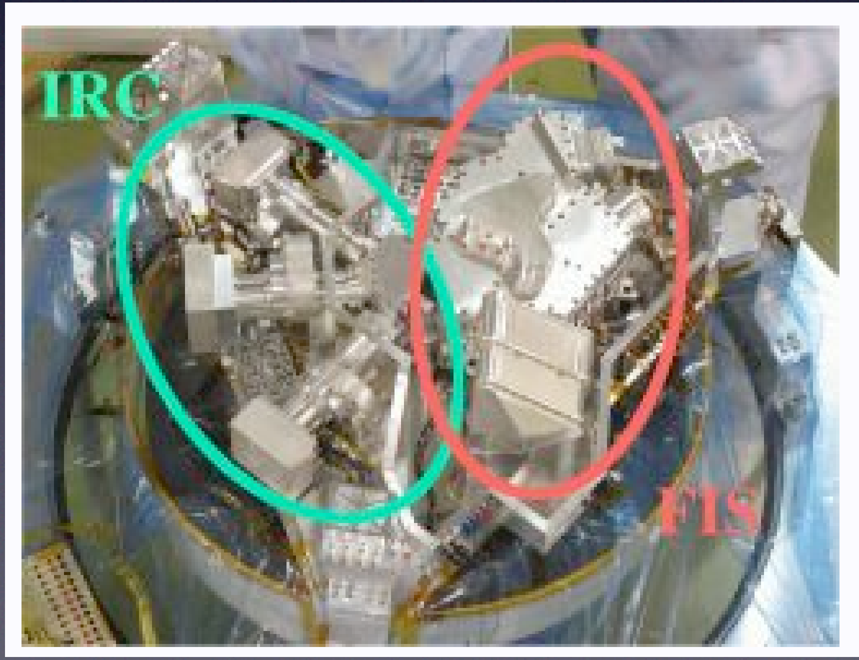




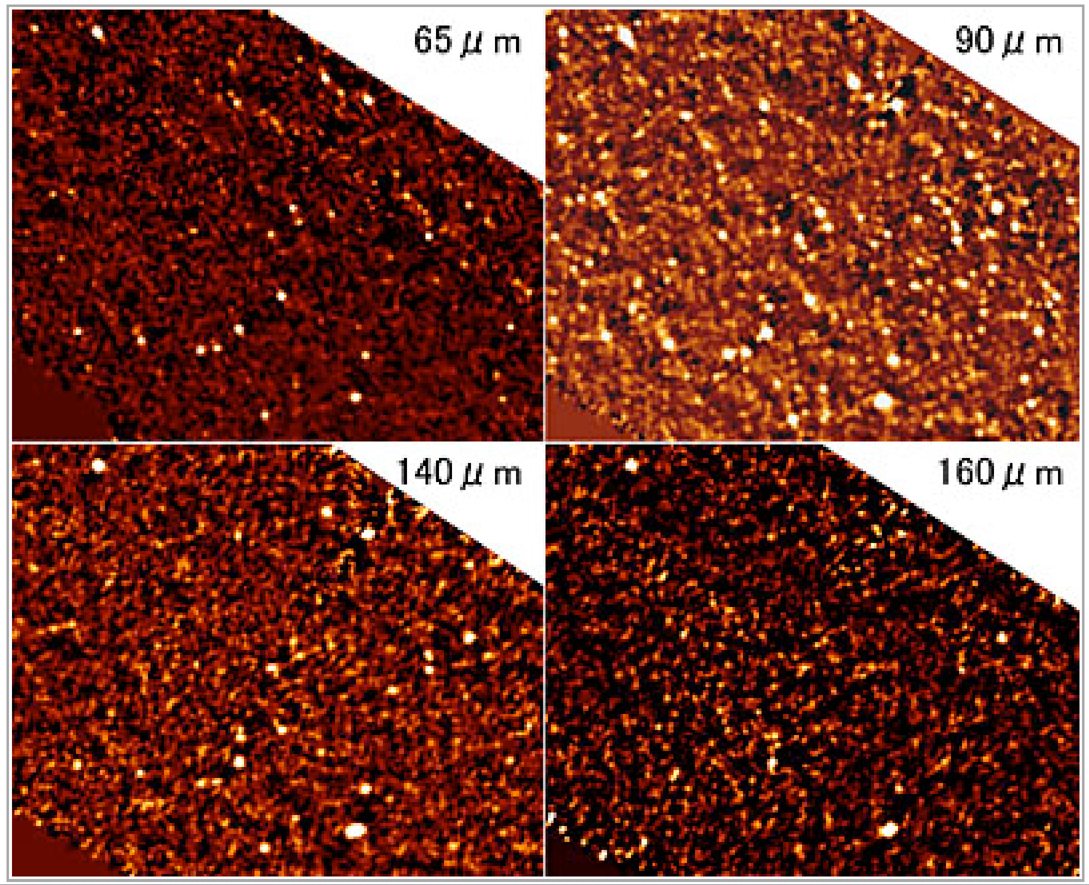
Last topic:

Akari - “uber-IRAS”





Band Name	N60	WIDE-S	WIDE-L	N160
Wavelength(micron)	50-80	60-110	110-180	140-180
Detector	Ge:Ga		Stressed Ge:Ga	
Array Format	20x2	20x3	15x3	15x2
Pixel Size(arcsec)	26.79		44.20	
Pixel Pitch(arcsec)	29.47		49.11	
Readout System	Capacitive Trans-Impedance Amplifire (CTIA)			
Sampling Speed(Hz)	25.28		16.86	



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Combining with Planck high-frequency channels probably improves further...

Future work (with *Planck*)

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* Akari dust map: better resolution, better T_dust, better point source subtraction. -> better dust template for *Planck*.